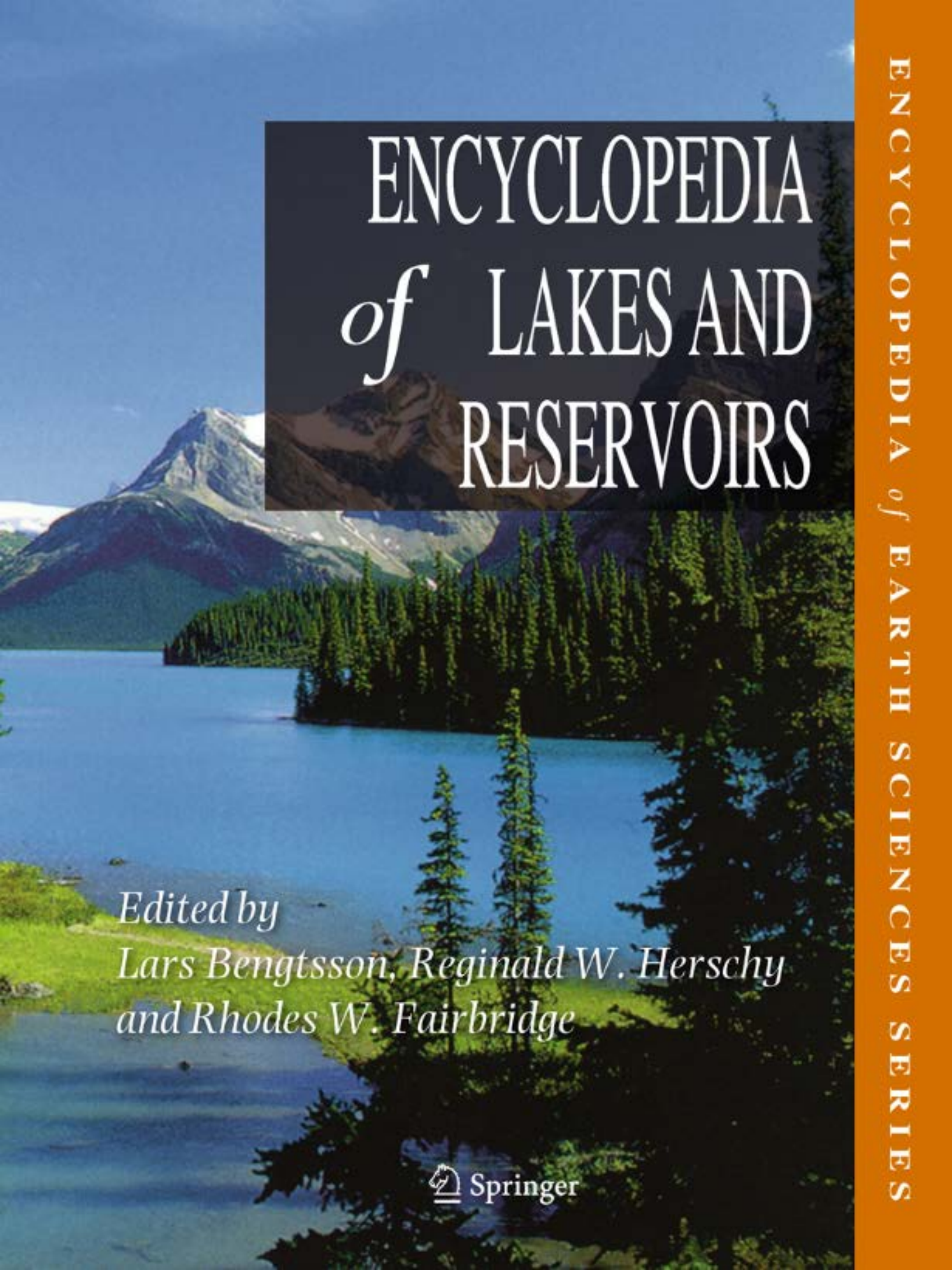


The background of the cover is a vibrant landscape photograph. In the foreground, there are dark green evergreen trees. Behind them is a calm, blue lake. The far shore is lined with a dense forest of green trees. In the background, majestic mountains with patches of snow rise against a clear blue sky. The title is overlaid on a dark grey rectangular box in the upper half of the image.

ENCYCLOPEDIA *of* LAKES AND RESERVOIRS

*Edited by
Lars Bengtsson, Reginald W. Herschy
and Rhodes W. Fairbridge*

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ENCYCLOPEDIA OF EARTH SCIENCES SERIES

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Preface

Lakes are formed when depressions are filled with water. Reservoirs are artificial lakes created behind a dam or between dykes. There are nearly nine million lakes in the world with a total surface area of about 1,600,000 km² and a total volume of 230,000 km³. In this encyclopedia, a lake is referred to as a water body with an area of at least 2 ha. Smaller water bodies are referred to as ponds and outnumber the lakes. Lakes and reservoirs are used for many purposes such as for water supply, fishing, recreation, irrigation, aquaculture, transportation, and receiving waters. Most of the large lakes and reservoirs in the world are described in detail in this encyclopedia. Smaller lakes are presented based on regions or countries. Also included are wetlands such as bogs, fens, and coastal marshes. Since the processes in semi-closed coastal basins are similar to those in lakes, estuaries and coastal lagoons are also discussed in this encyclopedia.

Most lakes are freshwater lakes, but by far the biggest one, the Caspian Sea (370,000 km²), is a salt lake with its surface below the sea level. Many lakes are situated in the northern part of the Northern Hemisphere, and were created when water filled depressions formed as the land ice retreated. These lakes are usually rather shallow and often situated clustered together. Lakes formed by tectonic uplift can be millions of years old. Lake Baikal is believed to be 20 million years old. However, a lake does not exist forever. Sediments from rivers can fill the lake, which becomes shallower and in due course becomes a wetland and finally a forest. This process takes thousands of years. Under the influence of humans, the process may be accelerated when lakes are loaded with nutrients.

Reservoirs have been built for some 5,000 years in different parts of the world, the oldest dam being Sadd el-Kafara built about 2,800 BC in Egypt. One of the oldest reservoirs still in existence today is Mannoh-Ike in Japan built in the ninth century AD.

Different physical, chemical, and biological processes take place in lakes, the most important, perhaps, being

the water balance, which refers to the balance between inflows and outflows and water storage. The water quality in a lake is determined, to a great extent, by the conditions in the upstream river basin. Within the lake, the water circulates and mixes with the help of the wind and solar radiation. A lake may receive several pollutants from human activities. The thermal conditions within a lake largely determine how different waters are mixed, and together with the light conditions and the nutrient status influence the primary production and biological life. All these processes are very different in shallow lakes and in deep lakes and also vary between small and large lakes.

Most lakes have an outflow that helps regulate the lake's water level. However, there are some low-lying lakes with no outflow. These terminal, or endorheic, lakes are very sensitive to climate variation and to human activities within the upstream river basin. A small change in the river inflow results in changed water level and consequent change in the lake area. This is seen clearly in the Dead Sea and the Aral Sea, where the lake areas have been reduced considerably. Terminal lakes are usually salt water lakes, the Dead Sea being an extraordinary example.

The objective of the *Encyclopedia of Lakes and Reservoirs* is to present the current state of scientific understanding of various aspects of the earth's lakes. A comprehensive overview of diverse though interrelated topics is provided. There are about 200 entries. The encyclopedia takes on a rather physical-geographical approach in that the lakes are characterized from surface area, depth and their hydrological characteristics, water balance, thermal regime, and river basin conditions. For individual lakes, different aspects of water quality are also included; for many lakes, circulation processes are described as well. The basics of physical, chemical, and biological processes are covered in a large number of separate specialized entries. Most entries are presented in a way the reader can benefit from even if they are outside of his or her expertise. Some other entries are informative

while others are specialized at a high theoretical level. There are also many entries that deal with engineering issues, focusing on how to solve different problems. Effort has been made to provide comprehensive coverage of different aspects of lakes and reservoirs. However, processes that require advanced mathematics to quantify are not dealt with in great detail.

The physical processes that have been treated are circulation and mixing of different waters, light-penetration and formation of thermal stratification, ice growth, and sedimentation. Sedimentation and resuspension of bottom material influence the water quality in a lake to a great degree, since different substances are brought into a lake with materials in suspension. Sediments brought into reservoirs shorten the lifetime of reservoirs. Chemical and biological processes that have been covered include nutrients in different forms, carbon cycle, eutrophication, bacteria, and various types of aquatic vegetation. Water quality, health aspects, and environmental issues are treated in special entries but are also directly related to many of the lakes. The water quality in lakes is important as it determines how the water can be used and regulates the biological life of the lake. The influence of physical processes on the nutrient cycle and biological life becomes clear from the entries that describe the changing conditions in lakes in detail. Circulation, nutrient balance, light penetration, and carbon cycle are all key to determining the status of a lake. Multipurpose use, conflicts, and social and ecological impact of reservoirs are discussed in some entries. A number of entries cover paleolimnological studies of lakes, while some others deal with expected future conditions in light of climate change, which, along with global warming, is at the center of public debates, professional forums, news media, and political dialogue. Finally,

the dynamic development of the world's lakes is discussed in detail in this encyclopedia.

The *Encyclopedia of Lakes and Reservoirs* is structured for quick access to particular terms and concepts in self-contained entries. The many overview entries should arouse the reader's curiosity about the different facts, problems, and processes related to lakes and the influence of humans on lakes and reservoirs. It is hoped that the encyclopedia will serve as a reference to scholars and students; it will be a resource for hydrologists, geographers, geologists, climatologists, limnologists, ecologists, biologists, physical planners, and water resource engineers, as well as to those who are engaged in the agricultural and civil engineering, earth sciences, and other relevant fields. The entries in this encyclopedia are divided into three categories: A, B, and C. Entries in category A represent major divisions and review topics. These also serve to coordinate the scattered entries in categories B and C. Entries in category B constitute items that are typically textbook sub-heads. Entries in category C consist of mini entries that deal with definitions, concepts, and short explanations of various phenomena. Entries are presented in alphabetical order. If the reader cannot find a suitable entry, it is suggested they refer to the index, since the topic may be covered under a different heading or be part of a larger entry.

The creation of this encyclopedia, like others in the series, has been possible only because of the cooperation of our wholehearted contributors representing more than 30 countries.

Lars Bengtsson and Reginald W. Herschy
Editors-in-Chief
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A

ACIDIFICATION IN LAKES

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Definition

A lake can be considered acid or slightly acid when pH is below neutral (<6.5). More evident biological consequences will develop at $\text{pH} < 5.5$.

Acid lakes have either natural or anthropogenic reasons.

Natural acid lakes are situated near peat bogs in northern regions (mainly in Russia, Canada, USA, and Scandinavia). Peat bogs emit organic acids (fulvo and x acids), which cause lakes to become acid. Many of such acid lakes are without fish.

Acid lakes due to anthropogenic impact get a considerable input of acid rain (including dry deposition). Through burning of fossil fuels (especially coal) without proper emission control of acid substances large amounts of acid substances have been emitted. The major acid substance is SO_2 (H_2SO_4). Nitrous oxides (HNO_3) and chlorides (HCl) also have an impact. These substances emitted as gases can be transported long distances until they reach ground either in a wet or dry form. Also ammonium (NH_4^+) will have an acidifying effect although it is in most cases originally emitted as ammonia, which have no acidifying effect.

Soil through weathering has a neutralizing effect. If the soil is calcareous no acidification can occur due to acid atmospheric deposition. With a coarse soil of noncalcareous matter the situation is different. Especially when the soil cover is very thin above ground rocks or nearly nonexistent the neutralizing effect is strongly limited.

Together with direct acid atmospheric deposition to a lake and acid runoff to a lake, pH in a lake can be low.

Acidified soil will leach out aluminum and other substances (iron), which will precipitate in the lake. In the

precipitation phosphorus is adsorbed and will be put into the sediments. Potentially acid sensitive lakes have naturally rather low phosphorus levels. Increased leaching of mainly aluminum due to acidification will through precipitation put the phosphorus levels to even lower levels. The production in acid lakes is therefore very low.

Acid lakes except impact on algal growth have a negative impact on fauna. Animals dependent on a calcareous skeleton get problems. That has a negative impact on crayfish and fish at low pH levels.

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AFRICA, LAKES REVIEW

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Introduction

The African continent with its offshore islands covers 30.1 million square kilometers, the islands including the Canary Islands, Cape Verde group, Reunion, Mauritius, etc. There is also Madagascar, with 590,000 km², often classed as a “subcontinent.” Africa is bordered by the Atlantic on the West, the Indian Ocean on the East, and the Mediterranean on the North. The continent is bisected by the equator, extending from Gabon to southernmost Somalia. N–S it extends 8,000 km, from 37° North almost to 35° South. The mainland stretches 7,500 km, from 17° West to 51° East. In area, there is about twice as much in the northern hemisphere as in the southern.

Geologically, Africa is an integral part, the central part of the ancient Gondwanaland which started to break up about 250 Myr ago. The old continent had been brought together as a complex of still older Precambrian crustal blocks, united during the Pan-African orogeny about 550 Myr ago. Subsequent to that unification, each of the “tessera” blocks underwent a long history of alternating downwarping and uparching that created a megamorphology which defines the present-day drainage basins like the Congo (Zaire), the upper Niger, and the White Nile. Both East and West margins are truncated cratonic borderlands. However, the NW and South margins are marked by E-W orogenic belts, the southern one (the “Capeides”) dating from late Paleozoic folding, and the northern one (the Atlas/Maghreb ranges) from late Mesozoic and Cenozoic folding. Probably the most striking feature of African geotectonics at the present time is the East African–Red Sea rift zone, a global scale taphrogenic feature that is generally regarded as still-another fracture zone of the post-Gondwana breakup which may well anticipate a new oceanic seaway. These fractures tend to a zigzag pattern, resulting in star-like “triple-point” intersections. Where the South American continent broke away in the Gulf of Guinea, the third branch, a so-called failed arm (known as an “aulacogene”) is represented by the Niger delta and the lake-occupied Cameroon belt.

Volcanoes mark the mid-cratonic triple points in centers like the Hoggar in southern Algeria or the Tibesti at the Libya-Chad border. The East African rift zone from the Red Sea to Mozambique is dotted with volcanoes, many with highly alkaline lavas, which control the chemistry of nearby lakes. One totally unique crater is Lake Bosumtwi in Ghana, the impact site of a major asteroid.

Climatologically, Africa is dominated by its position astride the equator which coincides with the drainage basin of the Congo and is largely occupied by rainforest in the lower elevations though replaced in the higher eastern plateaus by forested savannas. Borders of the great rift valley lakes are marked by vertical environmental sequences, and some of the major volcanic slopes display a dramatic sequence passing upward through equable mid-latitude forest zones into tundra and eventually permanent snow fields (e.g., Mt. Ruwenzori, Mt. Kenya).

North and south, around 10–20° North and South, are the typical savanna lands that are visited regularly by the monsoonal rains as the heat equator shifts North or South. These rains often come in two wet seasons, once as the monsoonal front passes over and once as it returns. This savanna belt is very much more extensive in the northern hemisphere where it is known as the “Sahel,” extending from Senegal to Eritrea.

Likewise paired are the two high-pressure arid belts, the Sahara Desert in the north, the Kalahari in the south, though again the Sahara-Libyan-Arabian belt is far wider. Here we need to recall the long-term effect of the planetary orbital precession (of about 18,000/23,000 year) which switches the Earth’s closest approach to the Sun: now in

the southern hemisphere, but in the northern about 10,000 years ago. This had the effect then of bringing the monsoonal rains across the Sahara to the borders of the Mediterranean and many paleolakes are found here today. In most cases, these former lakes are traceable only by their diagnostic deposits and large accumulations of shells and the bones of now extinct creatures, fish, *hippopotamus*, crocodiles, and bird life. In a few cases, there are still natural springs that keep the lakes in existence as oases. According to the Egyptian astronomer Ptolemy, in the first century AD, there were occasional summer thunderstorms at the latitude of Alexandria that are not known today.

Mediterranean-style climates are found in the northern and southern fringes of Africa. In the north, the rains come in the early months of the year (January–March); in the south, the opposite (August–October). They respond to the cyclical nature of the prevailing westerlies. These are interrupted by occasional outbursts of polar anticyclones that may bring associated precipitation as far south as Morocco and Mauritania when the Western Sahara may become dotted with small ephemeral lakes. At the higher elevations of the Atlas Mts, snowfall is a regular feature of winter seasons. On rare occasions, these winter snows reach as far south as the mountains of Ethiopia, and even the Nile at the latitude of Cairo has been known to freeze.

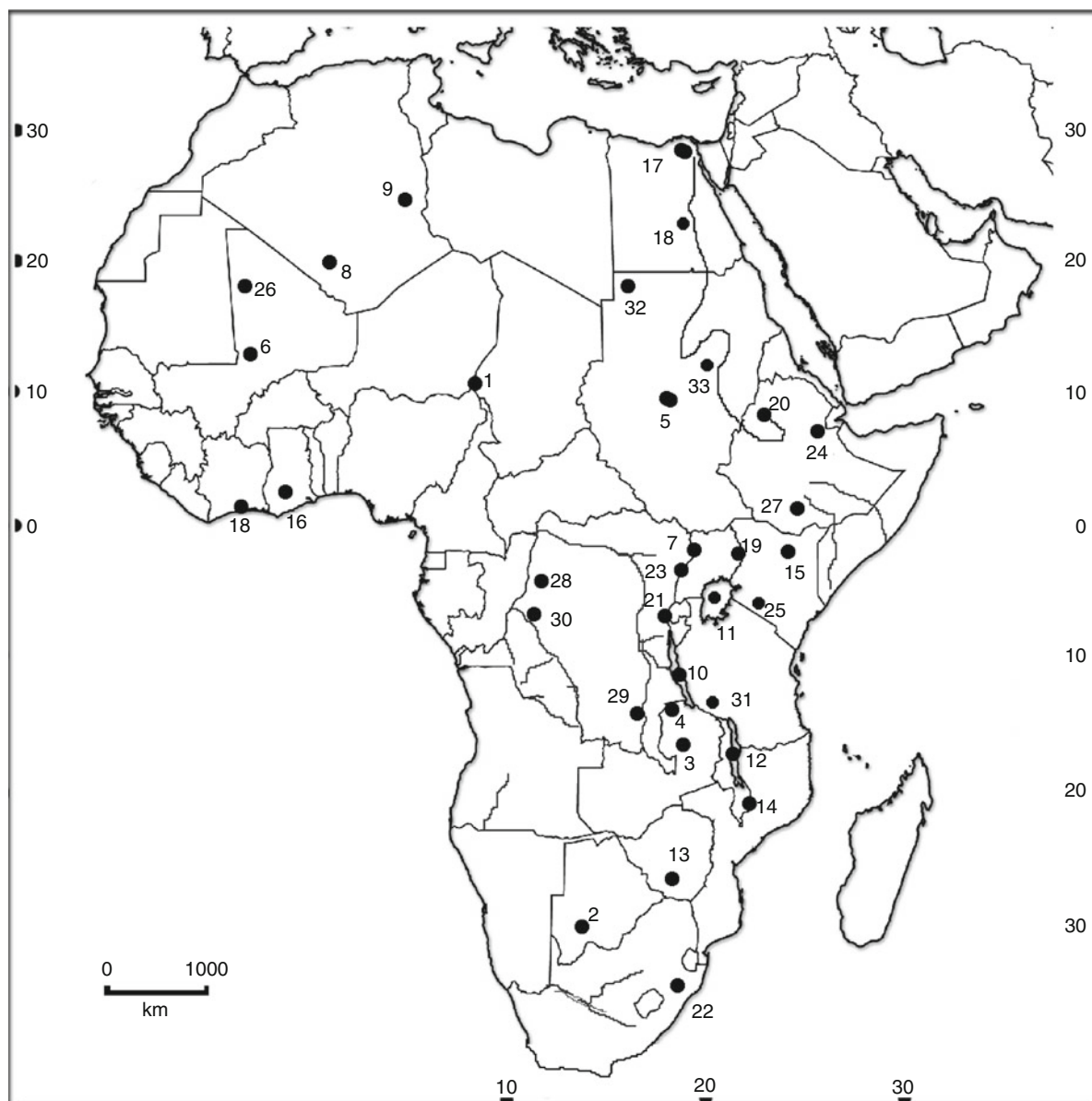
The coastal currents also affect the precipitation patterns. On the West, the S-setting Canaries Current is extremely cold, so that powerful temperature inversions bring arid conditions to the coast, and likewise in the South where the cold N-setting Benguela Current brings hyper-aridity to the Namib Desert of Namibia. In contrast, on the East coasts of Africa, the warm Mozambique Current brings heavy precipitation.

Political ups and downs make some of the citations rather confusing. Togoland, a former German colony, became divided, the West part being now attached to Ghana (1957) and the East part is now an independent state, Togo (since 1960). The French colony Dahomey (of 1844) has become Benin. The Belgian colony of Congo Belge became Zaire (in 1960), but has since reverted to “Congo.” The two lakes, “Lake Mobutu Sese Seko” and “Lake Idi Amin,” have both passed the way of all flesh. Lake Rudolf has become Turkana. Lake Nyasa (or Nyassa) and Lake Malawi are still undecided (Figure 1).

Classification of African lakes

Epeirogenic basins (broad downwarps of the Craton)

1. *Lake Chad*, Rep. Chad, Niger, and Nigeria (lake: 22,200 km²; drainage basin: 1,200,000 km²). Present inflow: 45.8 km³, fed by seasonal rains from Central African Republic, Niger, Nigeria, and Cameroon. No outlet (endorheic). It once reached from the Aïr to the Ouddaï, with an upper level 284 m above sea level, and an area approaching 300,000 km². Evaporation calculated at 2.26 m. During wet cycles of the geological past, a “Paleochad” existed that reached to the



Africa, Lakes Review, Figure 1 Distribution of lakes in Africa (After Herdendorf), 1, Chad; 2, Ngawi; 3, Bansweu; 4, Mweru; 5, No; 6, Debo; 7, Albert; 8, Hoggar; 9, Tassili n'Ajjer; 10, Tanganyika; 11, Victoria; 12, Nyasa; 13, Kariba; 14, Chilwa; 15, Rudolf; 16, Volta; 17, Aswan; 18, Aby; 19, Kyoga; 20, Tana; 21, Kivu; 22, Nhlange; 23, Edward; 24, Asale; 25, Magadi; 26, Faguibine; 27, Chamo; 28, Tumba; 29, Udemba; 30, Nai' Ndombe; 31, Rukwa; 32, Tibesti; 33, Ennedi.

margins of the present drainage basin. In 1995, an important discovery was made in Pliocene deposits that included an australopithecine, along with a rich fauna of mammals, fish, etc. which suggest a savanna with ephemeral rains.

2. *Lake Ngawi and Okavango Swamp*, Botswana.

Fed by multiple rivers from central Angola, lake expands enormously during southern rains, creating an interior delta, the Okavango Swamp. It has no outlet besides evaporation. Its biotopes are comparable with those of Lake Chad.

3. *Lake Joliba and others*, Mali. Seasonal lake related to the Niger's inland delta, which assumes major lake characteristics following the monsoonal rains.

4. *Lake Mweru*, in the Katanga which is the southern region of the Congo basin.

This lake has intake from the Chambezi in Zambia (explored by Livingstone in 1871), and its exit with many waterfalls emerges as the Luvua, and further downstream with the Lualaba. The latter is considered to be the principal source of the Congo. It receives some overflow from Lake Tanganyika.

5. *Lake No, and Nile Inland Delta, in the Sudd*, southern Sudan.

The Sudd is a swampy section of the White Nile (Bahr el Abiad in Arabic), which expands into an inland delta that has lake to swamp characteristics depending on the season. The northern end is marked by Lake No, a perennial feature.

6. *Lake Debo and Niger Inland Delta*, Mali. Comparable with that of the Nile, the Niger forms a giant ephemeral lake covering up to 20,000 km² in the wet season (October–December), its surface falling from 272 to 262 m above sea level. Lake Debo is in the lower section of the delta and is only 6 m deep at its maximum. Bounded on the NW side by the Saharan desert sands, at the high-water stage, the interdune depressions fill to create secondary lakes.

Epeirogenic upwarp centers

These include the Hoggar (Ahaggar) and Tassili n'Ajjer in southern Algeria, the Tibesti and Ennedi in northern Chad. Because of their elevations, they attract precipitation in the otherwise hyperarid regions of the Sahara. Radial wadis fill during rainstorms and feed into ephemeral lakes. Some rare, deeply scoured depressions maintain perennial water bodies, e.g., Djanet Oasis. They dry out into hard mudflats known as *sebkhas* (in the French-speaking regions; "*sabkhas*" in others). Examples in the area north of the Hoggar include the Tidikelt Plain with: *Sebkha Azzel Matti*, *Sebkha Meckerrhane*, *Azir*, *Chebbi*, etc.

Orogenic fold-belt lakes

In the depression between the Northern Atlas and the Southern Atlas of Algeria, there are extensive swampy or ephemeral lake bodies, e.g., *Chott ech Chergui*, *Chott el Hodna*, etc.

Also along the southern margin of the Atlas, there are numerous wadis that flow seasonally for 100 km or more and dissipate into the sands of the Sahara, or in some cases where there is structural subsidence, there are quasi-permanent chotts (also spelled "*schotts*"), *Chott Melrhir* and the *Chott el Djerid* (in Tunisia). The last named has connections to the Gulf of Gabes in the Mediterranean, and during positive eustatic oscillations, it has been inundated by the sea.

In the Western Sahara and southern Morocco, there are lower elevations which also catch some seasonal rains, feeding wadis that dissipate in large *sabkhas*, e.g., *Sebkhat Oum el Drous Guelebit*.

Structural troughs (taphrogenic, graben forms)

1. *Lake Tanganyika*, largest in capacity of the east African "great lakes," bounded by Tanzania, Congo (Zaire), Zambia, and Burundi, its area is 32,900 km² (12,700 mi²), while its capacity is 18,900 km³ (4,534 mi³) which reflects its tremendous depths (1,582 m, 4,823 ft). It is 773 m, (2,535 ft.) above sea level. Its length is 676 km (420 m). Its drainage basin is 237,000 km², fed by rivers along the rift valley,

notably the Malagarasi R. that debouches South of Kigoma. At the North end is the Ruzizi (Russisi) R. that carries the overflow from Lake Kivu. On the NE shore is the Kalambo R. which has a spectacular falls of 215 m (704 ft.), one of the highest in the world. There is a small overflow on the West side at Kalemle into the Lukuga to join the Congo above Kongolo.

2. *Lake Victoria*, largest lake (in area) in Africa; it is bordered by Kenya, Tanzania, and Uganda. It occupies a basin midway between the western and eastern branches of the Rift system. It has an area of 68,800 km² (26,563 mi²) with a volume of 2,700 km³ (649 mi³), being generally rather shallow. There are many islands, large and small. Its drainage basin is 190,000 km² which includes the ultimate source of the Nile, the Kagara R. The Nile's exit was formerly the Ripon Falls, to the Victoria Nile, but somewhat downstream (3 km) the Owen Falls hydroelectric dam at Jinja, built in 1954, controls the outflow (and submerged the Ripon Falls). Lake Victoria is at present 1,134 m (3,720 ft.) above sea level, but it fluctuated somewhat in time with the 11-year sunspot cycle, and in mid-Holocene time was more than 3 m higher.
3. *Lake Nyasa (Malawi)* is Africa's third largest lake, bordered by Malawi (former Nyasaland), Mozambique, and Tanzania, which is 30,044 km², marking the convergence of the eastern and western rifts, and 575 km (360 mi) long, while only 25–80 km (15–50 mi) across.

It is 474 m (1,555 ft.) above sea level, and its maximum depth is 695 m (2,280 ft.), thus 221 m below sea level. Its drainage basin is 94,100 km² (36,332 mi²). Its major intake is the Ruhuhu R. in the north, from Tanzania, which has considerable fluctuations, approximating the 11-year sunspot cycle, and causing oscillations of the lake level of up to 7 m. Its exit is via the Shire R. which is a tributary of the Zambezi. The name "Nyasa" simply means "lake" in the local language, but neighboring states seem to prefer Nyasa.

Lake Nyasa has existed in various forms since Cretaceous times and its early lacustrine sediments contain dinosaur fossils. Tertiary and Quaternary lake terraces occur at up to 300 m above the present lake surface. Lake Chilwa (Shirwa), about 130 km long, is located a short distance SE of Lake Nyasa.

4. *Lake Turkana (Rudolf)*, 6,405 km² (2,473 mi²), lies in the semiarid region of NW

Kenya, with a small overlap into SW. Ethiopia, being seasonally fed by the waters of the Omo River which rises in central Ethiopia, a drainage basin of 153,000 km² (59,060 mi²). Climate changes there have fluctuated greatly and former lake shores are found at over 100 m above the present level (375 m or 1,050 ft. above sea level). The depth is now 73 m. Its southern part is blocked by volcanic materials, and an ash cone was active as recently as the late nineteenth century. The area is of major interest for

paleoanthropology because of abundant traces of early Man and hominids, who clearly flourished in the formerly well-watered environments.

5. *Lake Albert*, 5,300 km² (2,075 mi²), is situated in the Western Rift and bordered by Congo (Zaire) and Uganda. It is sometimes called “Albert Nyanza” (as proposed by its discoverer, Sir Samuel Baker in 1864). The outlet to the North is through the Murchison Falls, after which, it is joined by waters from the Victoria Nile from the NE, and is then called the Albert or “Albertine” Nile, also known as the Bahr el Jebel (in Arabic). Its drainage basin is 18,000 km² (6,950 mi²) with an input of 24.9 km³ (6 mi³). Situated 619 m (2,030 ft.) above sea level, the depth is 50 m (168 ft.). The lake is 618 m (2,039 ft.) above sea level. To the South lie the Ruwenzori Mts (Ngaliema: 5,080 m, 16,763 ft.), that are said, according to Ptolemy, the Egyptian astronomer, to be the classical “Mountains of the Moon.” In the SW, it receives intake from waters of the Semliki R. which carries the overflow from Lake Edward.
6. *Lake Kyoga*, 4,429 km² (1,710 mi²), situated in the basin north of Lake Victoria, in Uganda. It is 80 km (50 mi.) long but only 8 m (25 ft.) deep. The Victoria Nile flows into it from the East and exits from the north. Its drainage area is about 75,000 km² (29,000 mi²). Its surface inflow is 24.1 km³ (about 5 mi³).
7. *Lake Kivu*, 2,700 km² (1,042 mi²), is located in the West rift between Lake Tanganyika and Lake Edward, with a drainage basin of 4,360 km² (1,680 mi²). It drains to the north to Lake Edward and south to Lake Tanganyika (Ruzizi [Russisi] R.). It is bordered by Rwanda and Congo. Measuring about 95 × 48 km (59 × 30 mi) at an elevation of 1,460 m (4,790 ft.), with a depth of 445 m (1,460 ft.), it is said to be the most beautiful of the Rift Valley lakes, at the center of a cluster of major volcanic cones, all above 3,300 m. Serious overpopulation leads to disastrous soil erosion.
8. *Lake Edward*, 2,510 km² (830 mi²), is situated between Uganda and Congo (Zaire), to the South of Lake Albert, with which its outlet is linked by the Semliki R. It is about 135 × 80 km (50 × 30 mi). Discovered by Stanley in 1889, it was once called “Albert Edward Nyanza,” and far to the NE, there is a connection with the smaller Lake George through the Kazinga Channel. The principal intake is from the Rutchuru R, sometimes taken as a western tributary of the Nile. Its drainage basin is approximately 20,000 km² (7,700 mi²) and is 912 m (2,991 ft.) above sea level. Several volcanic crater lakes exist in the vicinity, with no outlets and thus saline, one being the source of a salt industry.
9. *Lakes Asale (Assal) and Afdera* are hyperarid bodies located in the Eritrea/Ethiopian border area, in the Danakil Rift or Afar Depression, which is the extension of the East African Rifts in the Afars Triangle, thus leading into the Red Sea structures. Asale is the saltiest major lake (348 g/l), covering 57 km², at

155 m below sea level with a maximum depth of 40 m. The hydrology is seasonally fed by occasional rains in the eastern plateau (via the Kalou R.), but largely desiccated in the dry season. There are small, freshwater springs. The area is surrounded by glistening white salt flats notable for their spear-head crystals of gypsum, and encrustations of pink halite. Seasonally banded with fluvial sediments, the whole evaporite sequence is 20–80 m thick. The sale is exploited by Arabs who transport it as far as Tibesti.

10. *Lakes magadi (620 km²) and natron*, two shallow saline lakes resp. In South Kenya and North Tanzania, associated with large soda (trona) deposits. At several stages of the Pleistocene and Pliocene, there were large freshwater lakes here, apparently filled by much more abundant rains.

Volcanic lakes

Africa has at the present time no active subduction zone and thus no volcanic arcs. It has, however, mid-plate fractures and the rift zone where volcanoes are quite prevalent.

1. *Rift zone volcanoes* provide small crater lakes in several areas such as North of Lake Kivu in the West Rift, also near Lake Edward.
2. *Lake Tana* (Tana Hayk), 2,625 km² (1,400 mi²), the largest lake in Ethiopia, was created by lava flows which blocked the drainage system of the Little Abai R. It is 557 m (1,829 ft.) above sea level. The overflow into the Abbai proper becomes the headwaters of the Blue Nile (Bahr el Azraq in Arabic) which joins the White Nile (Bahr el Abiad) at Khartoum. Lake Tana is fed by seasonal floods during the monsoon.

Artesian-spring lakes

These are widespread in the Sahara, providing the basis for many oasis water supplies, and associated lakes. In the recent geological past (c. 2,000–10,000 year ago), a strengthened monsoon brought summer rains across the Sahara and paleolakes became abundant. They are dramatically identified today by former beach deposits and enormous piles of shells, fish bones and remains of major organisms including crocodiles and hippopotamus. Shrunken in size, a number of oasis lakes survive, e.g., in the Egyptian Western Desert: Siwa Oasis, several in the Qattara Depression, Bahariya Oasis, Farafra Oasis, Dakhla Oasis, and Kharga (the “Great Oasis”). At “*Lake Sitra*,” a paleolake in the Sitra Oasis of the Egyptian “Great Sand Sea,” there are freshwater deposits aged 38–19kyr ago. They correlate with similar paleolakes in NW Sudan and the Rub-al-Khali of Arabia. They occur at 9, 16, and 34 m above the present lake level. In the western Sudan there is the Selima Oasis, and the Merga Oasis in northern Darfur. Best known in eastern Libya is the Al Khufrah Oasis. In western Libya, there is the very remarkable “paleolake” of Ash Shati of interglacial age, found in the Fezzan area of SW Libya. Peripheral to the hilly areas here, there is a radial network of wadis that

run in wet seasons and then fill (temporarily) the normally dry ephemeral lakes. A good environmental indicator of the paleolakes is the bivalve *Cardium glauca*, a normally marine form adapted to seasonal salinity changes.

Coastal lagoons

These are extremely numerous, too common to enumerate, but a universal feature of the western coasts of the continent and the eastern, south of the Red Sea, where coral reefs tend to inhibit the wave action on littoral sands, needed to construct the littoral barriers. They are also infrequent along the more rocky Mediterranean shores.

Of interest is Lake Nhlangwe in Zululand, the largest lake in the Kosi system, where there is a 6–8 m terrace, 5 km W of the present coast. Its age is probably Eemian, and its environment a mix of marine and freshwater indications.

Dams and reservoirs

The oldest dams built for irrigation and flood control were those on the Nile, in upper Egypt (the Aswan Dam), and in the Sudan (Sennar Dam). These have been subsequently rebuilt or enlarged, the major one being the so-called High Dam (El Ali) at Aswan creating the *Lake Nasser* which reaches upstream into the Sudan as far as the Second Cataract.

Another major man-made lake is *Lake Volta* created in the state of Ghana, extending over half the length of the country. A third was created by the Kariba Dam and *Lake Kariba* on the Zambezi R. in Zimbabwe and Zambia. A fourth was built on the Atbara R., a major tributary of the Nile, situated in the Sudan near the Ethiopian border at *Khashm el Girba*, the lake being over 50 km in length.

The creation of inland seas, extensive canals and other water bodies subject to evaporation, has been proposed from time to time (e.g., see Lamb, 1977), but has been emphatically rejected by most hydrologists and geologists.

Cross-references

[Chad Lake](#)

[Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology](#)

[Victoria Lake](#)

AGE DETERMINATION OF LAKE DEPOSITS

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Synonyms

Chronology of lake sediments; Dating of lake sediments

Definition

Dating the depositional age of lake sediments and sedimentary rocks.

Dating methods

Lake sediments can be dated using absolute, relative, and/or radiometric dating methods. The different methods have different age ranges. Absolute dating methods are those that make use of counting of distinct annual and seasonal layers; these layers are preserved in lakes with anoxic bottom water conditions and absence of burrowing organisms and can be counted by the naked eye or under the microscope. Relative or age-equivalent dating methods compare specific events detected in the sediments (e.g., volcanic ash, biotic, geophysical, and geochemical changes) with the same events dated in another lake or elsewhere to create an age model. Comparisons and calibrations against the astronomical time scale are used for sediments or sedimentary rocks that are older than 150,000 years. Radiometric dating methods make use of the radioactive decay of isotopes (e.g., ^{14}C , ^{210}Pb). For dating young, up to 130-year-old lake sediments, natural (^{210}Pb) and artificial (^{137}Cs , ^{241}Am) fallout radionuclides are used. The most conventional method for dating the organic fraction in lake sediments 50,000 years back in time is radiocarbon (^{14}C), which relies on a progressive isotopic decay with time. The intensive use of ^{14}C dating since its introduction in the 1950s has led to a comprehensive understanding of the limits and potentials of this method, such as temporal or spatial variations in past ^{14}C levels and contamination of samples. To correct for temporal variations, ^{14}C dates are calibrated against internationally established calibration curves; to avoid spatial variations and contamination, only carefully selected terrestrial plant material is used for dating. Accelerator mass spectrometers now allow ^{14}C dating of material with a weight of < 1 mg. Other methods include, for example, U/Th dating of carbonate-rich lake sediments, infrared stimulated luminescence (IRSL) dating for mineral-rich lake sediments, or $^{40}\text{K}/^{40}\text{Ar}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic ash layers embedded in lake deposits.

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Cross-references

[Paleolimnology](#)

[Sedimentation Processes in Lakes](#)

ALPINE LAKES

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Definition

Thomas (1969) divides the central European Alpine lakes into the following groups:

1. Bavarian lakes situated on the Swabian-Bavarian plateau at about 500 m.a.s.l in calcareous-rich catchments; lakes in the Salzkammergut

2. Carinthian lakes, situated in mountains in the south of Austria; sample (1976) has listed 1,270 lakes above surface areas of 0.01 km²
3. Southern Alps (Italy and Switzerland mainly receiving water from crystalline regions of the Alps)
4. Lakes of the higher Alps usually of low salt content with a few being meromictic.

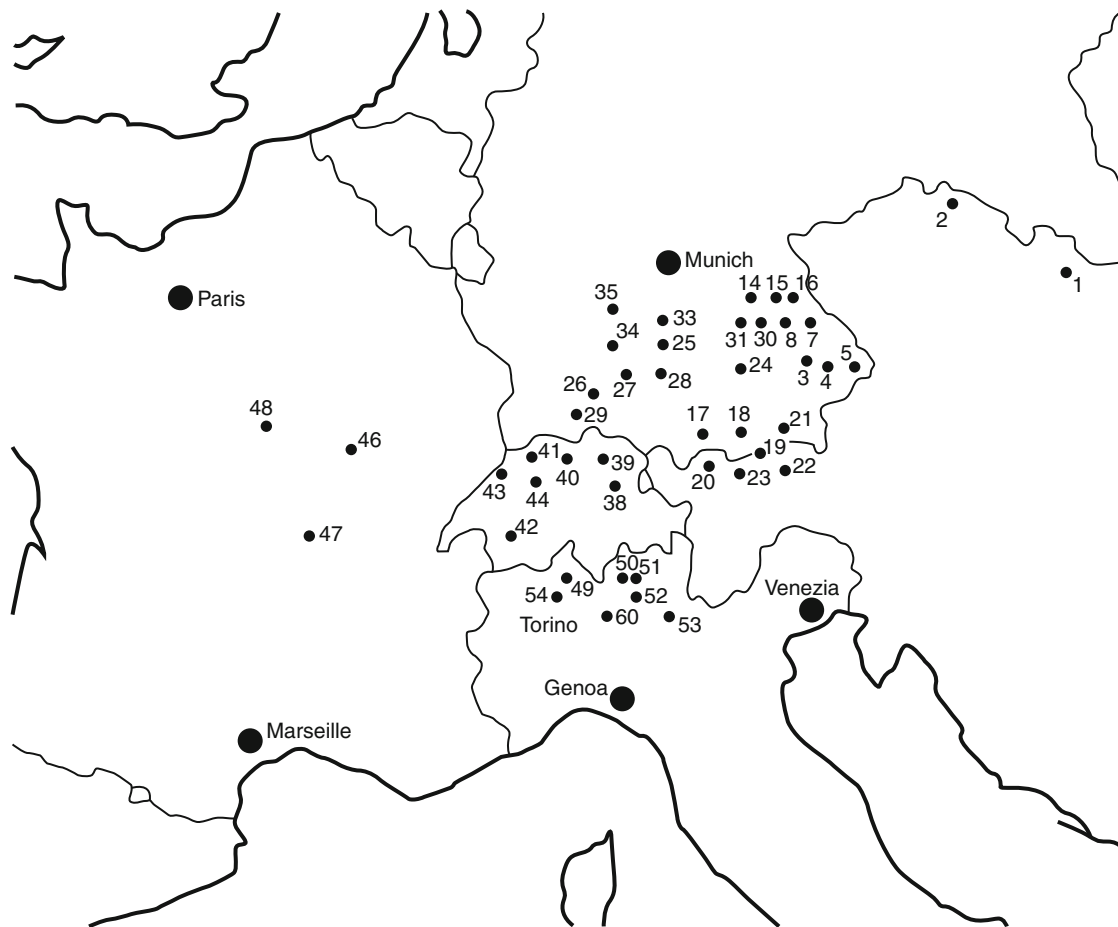
Dokulil (2005) has listed a selection of 60 Alpine lakes from the above groups in Table 1 and Figure 1.

Alpine Lakes, Table 1 Morphometric characteristics of 60 Alpine lakes: $Z_{\max}$ maximum depth, Z_{mean} mean depth, t_w theoretical retention time (Compiled from several sources)

Country/area	Lake name	Altitude (m.a.s.l)	Catchment area (km ²)	Lake area (km ²)	Volume ($\times 10^6 \text{m}^3$)	$Z_{\max}$ (m)	Z_{mean} (m)	t_w (year)
Austria	1 Erlaufsee	835	10	0.58	12.4	38	21.2	1.5
	2 Lunzer Untersee	608	27	0.68	13	33.7	20	0.3
Salzkammergut	3 Grundlsee	709	125	4.14	170	63.8	32.2	0.92
	4 Altauseersee	712	54.5	2.1	72	52.8	34.6	0.58
	5 Halstättersee	508	646.5	8.58	557	125.2	64.9	0.5
	6 Wolfgangsee	538	123	13.15	619	114	47.1	3.6
	7 Traunsee	422	1,417	25.6	2,303	191	89.7	1.0
	8 Krottensee	579		0.09	2.2	46.8	26	
	9 Fuschlsee	663	29.5	2.66	99.5	67.3	37.4	2.6
	10 Irrsee (Zellersee)	533	27.5	3.47	53	32	15.3	1.7
	11 Mondsee	481	247	14.21	510	68.3	36	1.7
	12 Attersee	469.2	463.5	45.6	3944.6	170.6	84.2	7.0
	13 Wallersee	505	110	6.39	71	24	9.4	2.0
	14 Obertrumsee	550	45.9	4.8	86	35	14.1	1.3
	15 Niedertumersee	500	12.5	3.25	48	40	14.8	3.1
	16 Grabensee	498	64.8	1.26	9	13	7.2	0.12
Carinthian Lake district	17 Millstättersee	588	276	13.28	1176.6	141	89	7
	18 Ossiachersee	501	154.8	10.79	215.1	52	19.9	2
	19 Wörthersee	439	164	19.38	816.3	85.2	42.1	9.5
	20 Weissensee	930	50	6.53	238.1	99	36	11
	21 Längsee	548		0.76	9	21	11.1	
	22 Klopeinersee	446	4.4	1.11	24.9	46	22.6	11.5
	23 Faaker See	554	35.6	2.2	32.7	29.5	14.9	1.2
Central Alps and Tyrol	24 Zeller See	749.5	54.7	4.55	178.2	68.4	39.2	4.1
	25 Achensee	929	218.1	6.8	481	133	66.8	1.6
	26 Piburgersee	913	2.65	0.13	1.8	24.6	13.7	2.7
	27 Vdr Finstertalersee	2,237		0.16	2.3	28.3	14.8	
	28 Gossenköllesee	2,413	0.3	0.016		9.9	4.7	
	29 Schwarzsee/Sölden	2,799	0.2	0.034		18	10	
Germany	30 Wagingersee		123.5	8.9	156.7	27	15.6	
	31 Königssee	603.3	137.6	5.3	511	189	93.1	2.3
	32 Chiemsee	518.2	1388.3	82.2	2053	73.4	25.6	1.4
	33 Tegernsee		210.5	9.1	324	72.2	36.6	
	34 Stamberger See	584.2	314.7	56.4	2,998	127.8	53.2	21
	35 Ammersee		988.5	47.6	1,775	82.5	37.8	2.5
	36 Bodensee	395	10,900	539	48,400	252	100	4.7
	37 Feldsee	1,109	1.5	0.9	1.4	32	15.7	0.5
Switzerland	38 Walensee	419	1061	24.2	2420	145	100	1.4
	39 Zürichsee (Ober S.)	408	1564.8	20.3	467	48	23	0.2
	40 Zürichsee (Unter S.)	406	1740.1	65.1	3,300	136	51	1.4
	41 Greifensee	436	160	8.5	150	32.6	17.7	1.5
	42 Vierwaldstättersee		1,831	87.8	12,280	214	156	1.8

Alpine Lakes, Table 1 (Continued)

Country/area	Lake name	Altitude (m.a.s.l.)	Catchment area (km ²)	Lake area (km ²)	Volume ($\times 10^6\text{m}^3$)	Z_{max} (m)	Z_{mean} (m)	t_w (year)
France	43 Baldeggersee	463	67.9	5.3	178	66	34	6
	44 Hallwilersee	449	127.7	9.9	285	48	20.6	4.1
	45 Sempachersee	504	62.6	14.4	624	87	46	17
	46 Lac L��man	372	7975	582.4	88,900	309.7	152.7	11.8
	47 Lac d'Annecy	446.5	278	27	1120	64.7	41.5	3.8
Italy	48 Lac Nantua	474.5	50.3	1.4	40	42.8	28.4	0.7
	49 Lago Maggiore	193.5	6599	212.5	37,700	370	177	4
	50 Lago Lugano	271	615		6,500	288	130	0.8
	51 Lago di Como	198	4,572	145.9	22,500	410	153	4.5
	52 Lago Iseo	186	1,842	61.8	7,600	251	123	4.1
	53 Lago di Garda	65	2,350	370	49,000	346	136	26.6
	54 Lago Die Mergozzo	194			83	73	45.4	4.7
	55 Lago di Oggione	225	12.7	3.8	24	11.3	6.3	1.6
	56 Lago Die Pusiano	260	90.6	4.9	69	24.3	14.0	0.8
	57 Lago di Montorfano	394	1.7	0.46	2	6.8	4.1	1.1
	58 Lago di Annone	225	14.5	1.7	6.8	10.1	4	0.4
	59 Lago de Segrino	374	3.4	0.38	1.2	8.6	3.2	0.3
	60 Lago d' Alserio	260	18.4	1.23	6.55	8.1	5.3	0.4



Alpine Lakes, Figure 1 Map of the Alps showing the location of 60 Alpine lakes. Their names and morphometric characteristics can be identified from [Table 1](#).

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Cross-references

[Carinthia Lakes and Reservoirs in Austria](#)

ALTERNATIVE STABLE STATES IN SHALLOW LAKES

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Synonyms

Alternate states; Alternative domains; Alternative structural regimes

Definition

Alternative stable states – One of several possible outcomes of dynamic modeling of complex systems, i.e., mathematical modeling of dynamical systems over time. Other outcomes include a single equilibrium and oscillations. In alternative stable states, each state is stabilized by feedback mechanisms. The system can, however, shift abruptly between the states by a gradual change in the independent variable when a critical threshold, a tipping point, is reached. Perturbations, i.e., external forces that alter the system structure but are not affected by the system, may also cause a system shift.

Tipping point – In dynamic modeling a critical threshold value of the independent variable where a system shifts to a contrasting state.

Hysteresis – The tipping point where the system shifts from one state to the other differs in value of the independent variable from the tipping point where the system returns to its original state.

Resilience – The ability of the system to withstand a perturbation, i.e., a temporal change of system structure, without changing state.

Introduction

Shallow lakes may change abruptly from lush submerged vegetation and clear water to phytoplankton dominance and turbid water, and vice versa. Such drastic changes not only affect plants but reorganize the entire biotic community and change physicochemical conditions and nutrient dynamics. During the 1970s–1980s, an accumulation of documented cases of structural shifts from a clear to

a turbid state lead to a conclusion that this dynamic is general to shallow temperate waters. These observations were in line with theoretical ecological work, suggesting that ecological systems may shift structure according to alternative stable state dynamics. The theory of alternative stable states in shallow lakes developed in the 1990s, and today shallow lakes are regarded one of the best studied examples of ecosystem with alternative stable state dynamics. In its original version, the model predicts that in shallow lakes two alternative states, a clear state and a turbid state, are possible within an intermediate range of nutrients, primarily phosphorus. The shallow lake ecosystem can shift state, either as a result of a gradual change in nutrient concentrations, e.g., eutrophication, or by perturbations that reorganize the system. Such perturbations can be, for instance, a large-scale removal of submerged vegetation through a storm event, or an altered fish community as a result of a stochastic fish kill or deliberate harvesting.

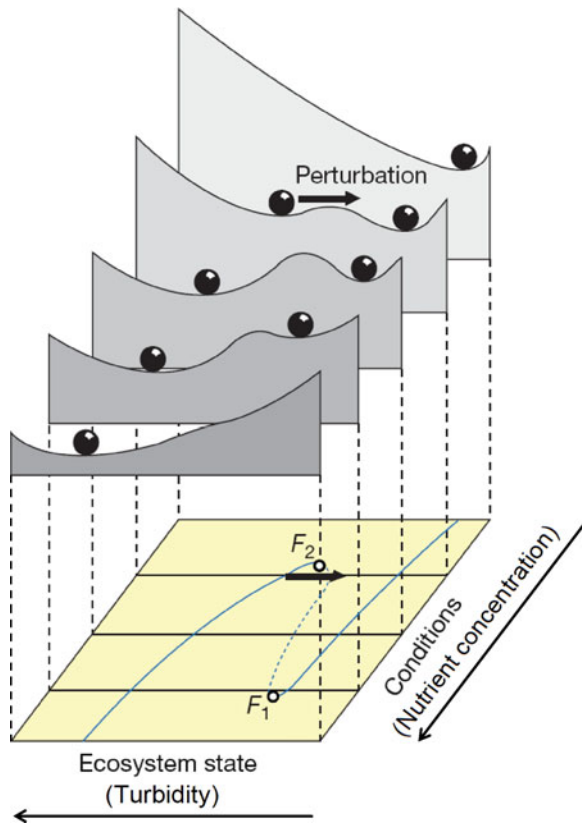
Theory of alternative stable states

Dynamic modeling of complex systems in some cases shows that the system can exist in two or more alternative stable states. The system is stabilized around these levels by negative feedbacks. A gradual change in the independent variable therefore results in a restricted effect on the state variable, until a threshold value is passed, a “tipping point,” where the system leaves the present state for an alternative state. The change can also be expressed as a system leaving the domain of one attractor and entering the domain of another attractor (Scheffer et al., 2009). As the system shifts from one stable state to the other it will pass an unstable equilibrium, in which the system is affected by a positive feedback that drives the transition. The stabilizing and destabilizing effects of the feedbacks on the system are often illustrated by the heuristic “marble-in-a-cup” model (Figure 1).

The possibility of alternative stable states in ecological systems has been suggested repeatedly through history, for instance, by Lewontin (1969); Holling (1973); Sutherland (1974); May (1977); and Scheffer et al. (1993, 2001). A model for alternative stable states in shallow lakes was presented by Scheffer et al. (1993). According to this model, two alternative states are possible within an intermediate nutrient range. Outside this intermediate range, only the clear state is possible at low nutrient concentrations and only the turbid state at high concentrations (Figure 2).

Empirical support for alternative stable states in shallow lakes

For reasons such as high degree of complexity and large temporal and spatial scale of the system, efficient experimental evidence of alternative stable states in natural ecosystems is scarce. In a critical review of experimental evidence for alternative stable state dynamics in

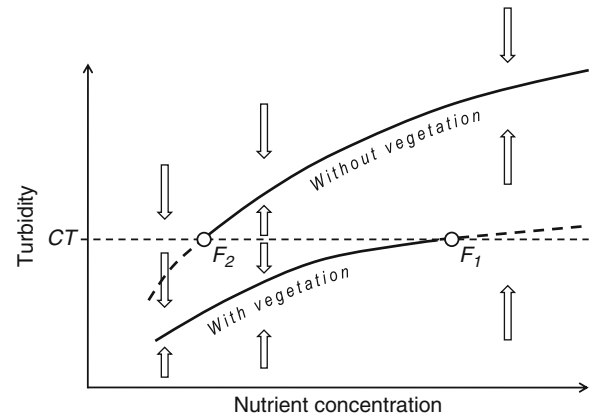


Alternative Stable States in Shallow Lakes,

Figure 1 Alternative stable states illustrated by the “marble-in-a-cup,” where the marble represents the system and the depth and shape of the “cup” the resilience of the state, i.e., how strong a perturbation has to be to force the system to shift. The lower surface area shows how the ecosystem state varies with the level of conditions. In this relationship, F_1 and F_2 represent “tipping points,” where a gradual change in conditions will cause a shift. Solid lines denote stable states, corresponding to the valleys in the three-dimensional graph above, while the dashed line, an unstable, transient state that corresponds to a hill in the upper graph. Note that alternative states are possible only within an intermediate range of conditions, whereas only one stable state is possible outside this range (Modified from Scheffer et al., 2001).

ecological systems, Schröder et al. (2005) concluded that although experimental evidence for alternative stable state dynamics was predominantly found in laboratory studies, there are no reasons to believe that natural ecosystems should be less prone to this kind of dynamics. Hence, indirect evidence of alternative stable states is in most cases the only realistic aim.

Empirical support for alternative stable states in shallow lakes is generally based on time series, correlational studies, and cross-comparisons. An example of a cross-comparison approach is tests of bimodal distributions among state variables, for instance turbidity, across sets of independent lakes and ponds (Jeppesen et al., 1990; Jackson, 2003).



Alternative Stable States in Shallow Lakes,

Figure 2 Alternative states of turbidity as a function of nutrient concentration in shallow lakes with and without submerged vegetation. The horizontal dashed line denotes a critical turbidity (CT) and “tipping points” (F_1 and F_2 , see Figure 1), where the vegetation disappears with an increase in nutrient concentration and returns with a decrease. Note that outside the nutrient range between F_1 and F_2 , only one of the states is stable, indicated by a dashed part of the line as it passes CT. The arrows show the direction of change in case the system is outside the alternative stable states (Modified from Scheffer and van Nes, 2007).

Examples of lakes that have changed abruptly include the Norfolk Broads in the UK (Moss et al., 1996), L. Veluwemeer (Meijer, 2000) and L. Zwemlust (Van Donk, 1998) in the Netherlands, L. Krankesjön and L. Tåkern in Sweden (Blindow et al., 1993), Tomahawk Lagoon in New Zealand (Mitchell et al., 1988), and L. Christina in Minnesota, U.S.A (Hanson and Butler, 1990). Among these cases, data from L. Veluwemeer are particularly interesting because Meijer (2000) could show that the disappearance and return of submerged vegetation during two shifts – from clear to turbid conditions and back again – occurred at different levels of total phosphorus, the independent variable, which indicated hysteresis in line with predictions based on the alternative stable state theory (Scheffer et al., 2001).

Empirical work on restoration of eutrophicated lakes by means of reduced nutrient loading has provided further support for the presence of hysteresis, as lakes often tend to remain in a turbid state, unless submerged vegetation can establish. Manipulations of lakes in order to reduce the effects of eutrophication have also resulted in improved understanding of fundamental feedback systems that tend to stabilize and destabilize the alternative states (Scheffer and van Nes, 2007). Although the aim of such projects has not been to test predictions generated by alternative stable state theory, they have nevertheless been useful in this aspect and contributed to a rapid development of the ecological theory of shallow lakes (Jeppesen et al., 1998; Scheffer, 1998).

Feedback systems in shallow lakes

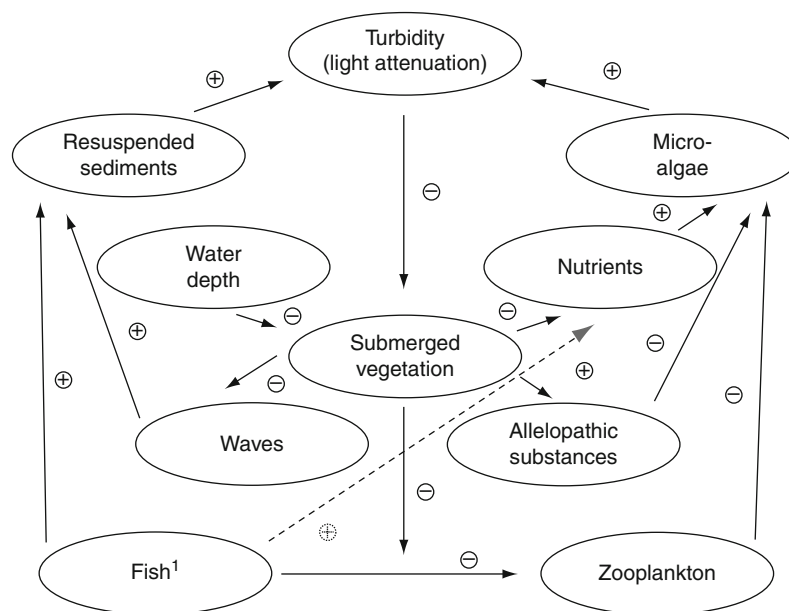
Feedback systems play a fundamental role for alternative stable system dynamics, as negative feedbacks stabilize the alternative states and positive feedbacks generate the rapid transition over the unstable state during a shift. If such feedback systems can be documented to have this impact on natural systems, these findings could be regarded as support for the idea that alternative stable states are part of natural ecosystems.

In shallow lakes, several feedbacks have been identified. Of these, some were previously known from the research field of trophic cascades in lakes (Carpenter et al., 1985). This food-chain-based model predicts that altered abundance of top predators such as predatory fish will cascade down the food-chain and influence phytoplankton density and water clarity through effects of intermediate trophic levels such as zooplankton-feeding fish and zooplankton. In shallow lakes, this means that increasing the abundance of predatory fish would promote submerged vegetation through a cascade of decreased biomass of zooplankton-feeding fish, increased abundance of filtering zooplankton, and, finally, reduced biomass of phytoplankton, and thus reduced turbidity. Because reduced turbidity means improved light conditions for submerged vegetation, the plant cover could increase. Increased vegetation and water clarity, in turn, is likely to improve the recruitment of predatory fish, such as pike and predatory perch, and a feedback loop is closed.

The negative relationship between submerged vegetation and turbidity has a central position among feedbacks that are likely to drive the alternative stable state response of the system to environmental change. This and other feedbacks were illustrated by Scheffer et al. (1993) in a graph showing known interactions between expected key compartments of the ecosystem (Figure 3). In this graph, feedback interactions between submerged vegetation and turbidity include two loops: the path over microalgae (phytoplankton as well as epiphytic microalgae) to the upper right (Figure 3) and the path over physical disturbance of the sediment surface to the upper left. In both loops, an increase in vegetation will tend to reduce turbidity, which in turn will promote the vegetation, resulting in a positive feedback. By contrast, in the absence of vegetation cover, a large proportion of the bottom area in a shallow lake can be subject to physical disturbance by waves and currents, resulting in wind-induced resuspension of sediment particles and high turbidity (Bengtsson and Hellström, 1992). The stabilizing effect of submerged vegetation on water clarity thus results from a number of biotic and abiotic mechanisms.

Past and present research

The theory of shallow lake dynamics has developed rapidly in conjunction with a growing understanding of ecosystems, gained from large-scale management projects aimed to reduce the ecological effects of anthropogenic



Alternative Stable States in Shallow Lakes, Figure 3 A conceptual framework of compartments and interactions behind the non-linear dynamics of shallow lakes. The negative and positive signs indicate expected effects by one compartment on the next one in the direction of the arrows. Feedback loops can be identified by following a series of compartments and interactions along the direction arrows.¹ Fish denotes the functional group of invertebrate feeding fish, i.e., feeding on zooplankton or substrate-dwelling invertebrates such as insect larvae, snails, and crustaceans (Vanni, 2002). The dashed line shows the effect of nutrient excretion, an important effect of fish that was not well studied at the time the original figure was presented (Modified from Scheffer et al., 1993).

eutrophication (Hansson et al., 1998; Mehner et al., 2002). The exchange of knowledge has worked both ways, as alternative stable state theory has influenced water management. Besides the applied use of the stable state theory in the management of shallow lakes, the improved understanding of shallow lake dynamics has also contributed to the understanding of ecosystems in general. Alternative stable state dynamics has been proposed to explain observed alterations in a wide range of ecosystems, including for instance rangelands, deserts, ocean communities, and coral reefs (Scheffer et al., 2001; Folke et al., 2004). Among these ecosystems, shallow lakes still remain one of the best studied (Scheffer and Carpenter, 2003).

Lately, the theory of shallow lake dynamics has developed further to include the possibility of more than two stable states (Scheffer et al., 2003), conditions that cause cyclic shifts (van Nes et al., 2007), and the notion that certain cases of apparent alternative stable state dynamics may actually be the result of slow transients from frequent perturbations (van Geest et al., 2007; Scheffer and Jeppesen, 2007). Because of the difficulties to predict a forthcoming shift and to reverse the process in these kinds of systems, there is a need to be able to manage systems so that they are robust against perturbations. For the same reasons, it is important to develop monitoring parameters that provide early warning signals of lowered resistance to perturbations and thus increased risk of a shift to a less desirable state (Scheffer et al., 2009).

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Cross-references

Aquatic Plants
 Eutrophication in Fresh Waters: An International Review
 Hydrodynamics of Very Shallow Lakes
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 Wind Waves

AMAZON LAKES

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Introduction

With $\sim 6,200,000 \text{ km}^2$ of drainage area mainly covered by the Amazon rainforest and discharging near 18% of the total flow of fresh water to the ocean, the Amazon fluvial system continues to intrigue naturalists across the world.

Carrying an average water discharge of more than $200,000 \text{ m}^3 \text{ s}^{-1}$ and a sedimentary load that could oscillate between 1 and 2 billions of tons per year to 614 Mt year^{-1} at Obidos, close to the mouth (Meade, 1994; Filizola and Guyot, 2009), the Amazon river is the largest and most peculiar fluvial system of the world with respect to water discharge. The Amazon rainforest, the largest tropical forest in the world, originally occupied more than 5 million km^2 spreading mainly over the Amazon fluvial basin. Humid tropical climate prevails, and rainfall averaging 2,000 mm/year increases in the northwestern direction and in some parts of the Sub-Andean zone to more than 5,000 mm/year. Although the rainforest extends into various countries, $\sim 70\%$ of the total originally forested area was located in Brazil. In reality, the Amazon region is a complex mosaic of different vegetation types, including closed rainforest, flooded forests, campina forests, savannas, bamboo forests, mangroves, montane and sub-montane forests, and liana forests (Murca-Pires, 1984; Witmore and Prance, 1987).

The Amazon fluvial system is characterized for supporting the most extensive floodplain system of the planet comprising a fascinating mosaic of wetlands and floodplain lakes, which sustain a huge biodiversity and have a main role in the emission of carbon dioxide and methane to the atmosphere. In fact, the Amazon fluvial system functions as a major collector to the water and sediments of a large variety of tributaries. Large tributary systems such as the Madeira, Negro, Japurá, Tapajos, Purus River, and others rank between the 20 largest rivers of the planet (Latrubesse et al., 2005; Latrubesse, 2008).

Lakes are a main source of information to understand the quaternary paleogeography and paleoecology of the Amazon as well as key pieces to understand the present-day “physiology” of the environmental system. This chapter focuses on the lake record in the basin since the Late

Cenozoic, attempts to understand the role lakes play in the basin, the main mechanisms generating them, their present distribution, as well as the environmental effects of dams and planned dam construction.

Lakes in the Amazon: When the jungle feeds amazing theories

As in other parts of the world considered “exotic,” by both the scientific community and the public in general, the Amazon has fed several fantastic theories concerning the interpretation of its Late Cenozoic paleogeography. Since the times of the Spanish and Portuguese empires, the fantastic Lake Paraima, supposedly located in northern Amazonia, inhabited in the imagination of conquerors dreaming with the “El Dorado.”

The mythological existence of a huge lake in the Amazon basin has persisted up to recent times. The actions of catastrophic floods as well as the existence of a huge lake and marine incursions were typical theories that produced immediate response in the media and, curiously, in part of the scientific community devoted to natural sciences.

Examples include the 1980’s megafloods theory, which postulated that the southwestern Amazonia was erased by megafloods coming from the Andes in response to the fluvial captures of the large Late Pleistocene Bolivian Altiplano lakes (which extended covering the Titicaca and Salar de Uyuni basins) (Campbell and Frailey, 1984; Campbell et al., 1985) and that a huge lake developed in the Amazon during the Late Pleistocene spreading on the lowlands (Frailey et al., 1988). According to this theory, this lake would have occupied an area larger than the Mediterranean Sea during the end of the Pleistocene, where today we have the richest and most extensive tropical rainforest and the main fluvial network of the planet.

More recently, it was postulated the existence of weak marine transgressions reaching the northern Amazonia during the Late Miocene (Hoorn, 1993). In addition, based on outcrops descriptions of the uppermost levels of the Solimões Formation in Acre territory (southwestern Amazonia), it was proposed that a huge seaway, connecting the Caribbean Sea with the Parana basin all across the South America and crossing the Amazon was installed in the continent during Late Miocene time (Räsänen et al., 1995).

Interestingly, no researcher has found any unequivocal evidence of marine environments in the sediments of the Solimões Formation, the geological unit that is being thoroughly investigated through outcrops and boreholes by geologists, paleontologists, geochemists, and other earth scientists.

While concrete Late Miocene marine environments does not appear in the geological record, some authors have resuscitated and adapted the mega-lake hypothesis in the Amazon, which occurred, instead, during the Middle-Late Miocene. This mega lake, named Lake Pebas, could occupy nearly all the lowlands of the Amazon basin west of the Purus Arch, i.e., roughly all

the lowlands territory located west of Manaus (Wesselingh et al., 2002; Hoorn, 2006).

Very likely, the Pebas mega-lake is “more of the same.” An alternative and more realistic scenario for the Late Miocene of the Solimões Formation consists of a paleoenvironmental model formed by a mosaic of wetlands, active and abandoned fluvial belts, lakes, and floodplain areas (some drier, with development of paleosols); i.e., an area dominated by complex mega-fan hyperarid rivers, floodbasins, and other wetlands areas (isolated swamps and lakes of several sizes) in a mosaic of environments as observed nowadays in several wetlands of the world and somewhat analogous to the Chaco and the Pantanal of Mato Grosso-Paraguay axis today (although the Amazon was wetter during the late Miocene than good part of Chaco) (Latrubesse et al., 2007, 2010).

Where are the lakes in the Amazon?

In spite the fact the Amazon is the largest fluvial basin of the world, located mainly in the humid tropics, the significance and extension of lakes is not so much spectacular as one could expect.

There are no huge lakes in the Amazon. Lakes are restricted mainly to particular geomorphic features in uplands and plateaus or developed as a consequence of fluvial processes in floodplain environments. The largest lakes are in reality flooded fluvial valleys.

A tentative classification of the lake system is shown below. It is possible to differentiate four main categories, including some flooded areas that are not “typical lakes.”

- (a) Lakes developed on older terrains without direct relation to the fluvial systems
- (b) Lakes developed in fluvial valleys and soft quaternary sediments but not directly related to fluvial landforms
- (c) Lakes generated by fluvial processes
- (d) A variety of wetland (and not really typical) “lakes”

Lakes developed on older terrains without direct relation to the fluvial systems

This kind of lake is mainly developed on older Precambrian rocks, affected by intense chemical weathering along the geological time. There is scarce information about the geomorphic processes generating these lakes, usually located on regional surfaces of plantation, often topped with thick laterite crusts, currently undergoing dismantling. Of course, whenever limestone is present, carstic processes can generate a mosaic of small lakes. Lakes can also be generated by “pseudo-carstic” processes, related to the dismantling of the laterite crust or to a more impermeable saprolite associated to the existence of conjugated fractures and the action of subsurface flow of the water table following the regional slope. Similar processes have been studied in some detail by the author in the Cerrado (savannas) area of Central Brazil and in the Cerrado-Rainforest ecotone.

A particular case regards the Carbonatic intrusive rocks which remain as isolated hills above the predominant lowered substrate of the Regional Surfaces of Plantations. A good example is the Six Lakes hills in the northern Amazonia (Amazon State), where the Carbonatitic rocks were deeply altered by more than 180 m of tropical weathering processes and body lakes were generated by dissolution processes.

The quaternary record

The main record of Quaternary palynology of the Amazon basin includes a marine core of the Amazon cone and five points from the following lakes: Carajás (6°S, 50°W), Hill of Six Lakes (0°16'N, 66°4'W), Maicurú (0°30'S, 54°14'W), Laguna Bella Vista (13°37'S, 61°33'W), and Laguna Chaplin (14°28'S, 61°04'W).

In the state of Para, in a little lake on the Carajás Plateau, dry periods were recorded with replacement of rainforest by savanna at 60 kyear, 40 kyear, and 23–11 kyear BP (Absy et al., 1991). All the records show a hiatus in sedimentation between ~23,000 and 13,000 14 C year BP (Carajás), ~32,000 and 12,000 14 C year BP (Pata), or between 25,690 and 17,410 14 C year BP (Maicurú), and 38,600 and 11,030 14 C year BP (Laguna Bella Vista). These hiatus are associated with a lack of deposition of organic material during thousands of years (Ledru et al., 1998) and/or strong erosive conditions. Laguna Chaplin presents a condensed sedimentary or a probably not continued sequence of sedimentation between 31,000 and 9,000 year BP. Presence of tropical semideciduous dry forest at the Cerrado–rainforest boundary in northeastern Bolivia (Bella Vista: Mayle et al., 2000) was documented at ca. 30,000 year BP after which a sedimentary hiatus was recorded lasting until the beginning of the Holocene and tropical rainforest could appear in the area by 2,740 year BP.

This small palynological record together with another locality in alluvial sediments in Rondonia (Catira Site) (Van der Hammen and Absy, 1994) were enough to keep a strong discussion on the Last Glacial Maximum Amazon paleoclimatology and paleogeography of the basin during at least two decades, between palynologists of different groups. However, because of the hiatus existing in the sedimentary record no pollen was recorded during good part of this period. All these studies used similar approaches, consisting of drilling lakes without record and mapping of Quaternary landforms and deposit, i.e., without additional observations or correlations with the sedimentary and geomorphologic units and landscape ecology for each region.

With exception of Hooghiemstra and Van der Hammen (1998), the majority of the palynologists either ignored or misinterpreted the abundant geomorphologic, sedimentologic, and paleo-vertebrates information obtained in the Amazon basin during the last two decades, relying only on the palynological record (see Colinvaux et al., 2000; Mayle et al., 2000; Bush et al., 2004; Anhuf et al., 2006,

among others). Interpretations taking into account just a local record and one “proxy” indicator (pollen) have produced a significant drawback in the understanding of the Quaternary climatic changes of the South American tropics, in special in the Amazon basin.

Lakes developed in fluvial valleys and soft quaternary sediments but not directly related to fluvial landforms

Rounded small lakes, permanent and mainly seasonal, are recorded in Roraima plain, northern Amazonia (Latrubesse and Nelson, 2001). The flat area cribbed by a large number of shallow depressions was affected by aeolian activity during the Late Pleistocene and Holocene. Very dissipated dune fields are recorded in this flat area forming the uppermost units of the Boa Vista Formation (Latrubesse and Nelson, 2001; Teeuw and Rhodes, 2004).

The lakes are circular, pear-shaped, or otherwise rounded in form and small in size – tens to hundreds of meters in diameter. The temporary lakes are affected by frequent grass fires in the dry season. They are consequently bare of woody vegetation, developing only a thin seasonal herbaceous cover. Some of the permanent lakes, however, contain dense communities of rooted shrubs. Depressions with open water or bare damp soil are also distinguishable from the surrounding non-flooded grasslands.

In the Cauamé dune field, the damp depressions are largely elongated and parallel to the prevailing NE-SW wind direction which generated dunes. Closed contours are taken to be the result of deflation behind apices of parabolic dunes followed by incomplete erosional fill-in or a remnant damming effect where younger slip faces once advanced up the deflation corridor of older dunes. In other parts of the sandy and silty realms of the Boa Vista Formation, the depressions are connected by a reticulate system of channels, or are chained like a string of pearls along a single valley. These landforms may be originally circular blow hollows or pans produced by ascendant helicoid winds active in a drier climate, during the hours of greatest solar heating. Circular blow hollows or small rounded pans are active where the water table is low; the soil has a low water retention capacity and sediment is unconsolidated. Circular blow hollows may also have reworked the elongate depressions of the Cauamé parabolic dune field, making them more circular or creating strings of broadened circular depressions along an elongate valley originally entrained by the deflation troughs of a stabilized parabolic dune. Such circular expansions and the development of an interconnected drainage field can explain why the elongate dune axes are difficult to detect in remote sensing products. The blow hollows now occupied by temporary or permanent lakes are inferred to have formed during a Holocene relatively dry phase (middle to lower Holocene) evolving from a mixture of hydro-eolian conditions. Present wet conditions favor dissolution processes on the oxidized sediments of the Boa Vista Formation and maintenance of lakes.

Lakes generated by fluvial processes

The Amazon Rivers can be classified roughly into two main groups due to the sedimentary load they carry and in several subgroups, according to their geological setting and the geomorphology of the channels and floodplains.

Regarding the geologic–geomorphologic context, tropical rivers flowing along fluvial linear belts can be grouped in orogenic mountains belts, Paleozoic and Mesozoic sedimentary plateaus/platforms, Precambrian cratons, lowland plains in sedimentary Cenozoic basins, and mixed terrains (Table 1) (Latrubesse et al., 2005).

Regardless the geology and relief they drain, rivers carrying abundant sediments (white water rivers) are rich in dissolved nutrients, while rivers carrying low quantities of sediments have high dissolved organic carbon and low levels of nutrients and other solutes (e.g., Negro River) or intermediate in solute contents (e.g., Tapajós River). The pH of the white water rivers typically varies between 6.5 and 7 while that of the black water systems varies between 4 and 5. Transparency (Secchi depths) in white water rivers range from 30 to 50 cm while in black rivers it can be up to 2 m (Furch and Junk, 1997). These values can change through the year as a consequence of water depth variations between high and lower water level stages. In terms of suspended sediment concentration white water rivers can oscillate between near 40 mg/l to values as high as 1,500 mg/l during peak discharges in the Madeira River, while than blackwater rivers such as Negro are characterized by values below 20 mg/l.

Floodplain lakes are generated by fluvial processes and are a component of the floodplain morphologies. In the case of the Amazon basin, the huge variety of channel patterns and the existence of complex (in time and space) floodplains induce a mosaic of lakes with large diversity in origin, shape, and functioning.

The floodplain along the Amazon main stem in Brazil (~2,800 km length) occupies approximately 92,400 km², of which 11% was estimated to be covered by 6510 lakes. However, only 10% of the floodplain lakes are larger than 2 km² (Sippel et al., 1992), with small lakes predominating over these landscapes.

Additionally, Sippel et al. (1992) estimated that the lower 400 km of the major tributaries occupy 62,033 km² and that the lake abundance and area of the four main tributaries (Negro, Purus, Japurá, Madeira) spreading in relation to floodplain range from 5% to 12%. For the same area of the Amazon system the mean flooded area between 1903 and 1996 was estimated in 46,800 km², of which river channels water and floodplain lakes comprised approximately 20,700 km² (Sippel et al., 1998).

Hydrologic modeling of the Amazon flooding wave along the main channel suggests that up to 30% of the main stem flow exchange water with the floodplain (Richey et al., 1989). The annual sediment exchange between the main channel and the floodplain on the basis of transport models should be more than twice the flux

Amazon lakes, Table 1 Geological and geomorphological settings for Amazonian rivers and main floodplain lakes types

Subcategory/description	Examples	Characteristic kinds of lakes
A. Rivers generating linear fluvial belts		
A1: Transporting low amounts of sedimentary load		
A.1.1. Precambrian cratonic areas: headwaters in areas of stable precambrian crystalline basement, low relief		
(a) Blocked valley, flooded valleys, very low suspended load	Tapajos, Xingu, Tefé, Coari	Blocked valleys lakes
(b) Wide valleys with islands alternating with narrow reaches with rapids or nodal points, very low suspended load	Negro, Trombetas, Aripuanã	Levee lakes and Igapó forests
A2 Transporting abundant sedimentary load		
A.2.1. Lowland plains in sedimentary Cenozoic basins	Purus, Juruá	Oxbows dominants
Single channel, nonharmonic meanders, muddy banks, high suspended load		
A.2.2. Mixed: Rivers draining mixed terrain		
(a) Platforms + cratons: mainly braided alternating with incised valleys, bed load dominant	Branco	
(b) Orogenic + platforms + cratons (+Lowlands): complex systems, mainly braided tendency, low anabranching, some rivers exhibit rapid alternating with wide alluvial reaches, high sediment load (suspended load dominant)	Madeira, Solimões, Amazon	Levee lakes, round floodplain lakes, island levee lakes, lakes generated by floodplain deltas, scroll lakes, abandoned channel lakes, scarce oxbows.
(c) Orogenic + Lowlands: well-defined headwater areas in orogenic belts and narrow alluvial plains, mixed morphologies (braided/meandering) along lowlands.	Japura, Ica, Mamore.	Oxbows, scroll lakes (Mamoré, Madre de Dios, Beni, Iça, Ucayali). Island levee, rounded floodplain lakes (Japurá)

through the river gauge located at Obidos, in the lower Amazon (Dunne et al., 1998).

However, the Amazon alluvial plain is stated to be not totally inundated during the typical flood season (Tricart, 1977; Iriondo, 1982). Mertes et al. (1996), using Iriondo's interpretation of landforms, estimated that, 40,000 km² of floodplain and 4,000 km² of islands are inundated by direct flooding of the Amazon, between Vargem Grande and Obidos. Some 20,000 km² of deposits of the alluvial belt remain dry or are flooded not by the Amazon but by small tributaries, groundwater seepage, or rainfall (Mertes, 1997).

More recently Hess et al. (2003), using JERS imagery, estimated that 17% of a 1.77 million km² study quadrat in Central Amazonia, which includes the main stem of the Amazon River from slightly downstream of the Napo River confluence to slightly downstream of the Tapajós River, the Negro River south of the Vaupes River confluence, and the lower reaches of the Tapajós, Trombetas, Madeira, Purus, Japurá, Juruá, and Iça rivers, are occupied by wetlands, which were 96% and 26% inundated at high and low waters, respectively. In relation to these figures, about half of the wetland area was occupied by floodplains and channels of the Amazon main stem and major tributaries. Hess et al. (2003) remarked that 70% of the wetland areas are constituted by flooded forest. The mapped classes of vegetation physiognomy and flooding status, however, show large variations because of floodplain geomorphology and with respect to white and black water environments.

Regional biogeochemistry lake analysis had concentrated dominantly along the main Amazon River tract.

An average thermal stratification of 1–3°C occurs daily in varzea lakes with a thermocline of between 2 and 4 m depth while a chemical stratification when water depth is larger than 4–6 m can be found in medium-size lakes (1–10 km²), producing anoxic conditions in the deeper water layers (Furch and Junk, 1997). Amazon floodplain lakes are usually undersaturated in dissolved oxygen and supersaturated in CO₂ because of the high respiration rates in the water column that exceed planktonic gross photosynthesis (Wismar et al., 1981; Richey et al., 1988; Melack and Fisher, 1983). Melack and Forsberg (2001), based on the total lake area of 10,370 km² estimated by Sippel et al. (1992) for the central Amazon floodplain, suggested an average areal production value of 300 t C km² year⁻¹ and estimated that the total gross production of phytoplankton should be 3.1 Tg C year⁻¹ (Tg = teragrams or 10¹² g). Macrophytes are also a main component on the floodplain and abundant in white water rivers lakes. A total regional net production of plants of 113 Tg year⁻¹ could be contributing to the primary production in the Amazon River floodplain in Brazilian territory, between approximately Tabatinga and Almeirim (Melack and Forsberg, 2001). From this total amount 65% is provided by herbaceous macrophytes and 32% by floodplain forest. Peryphitic algae could contribute with ~5% (Melack and Forsberg, 2001).

Nitrogen (N) and phosphorous (P) are adsorbed to suspended sediments of the Amazon River. It was estimated that up to 30% of available P may be adsorbed to clay, and N also can be provided significantly from local source particles (Engle and Sarmelle, 1990). Floodplain lakes lose N and P through several mechanisms such

as deposition of sediments, outflow to rivers and interconnected lakes, and groundwater seepage (Melack and Forsberg, 2001).

Amazon lakes that are closely connected to the channel morphodynamics and flood hydro-biogeochemical inputs are more alkaline and more oxygenated during flood stage. However, the hydro-geomorphologic mechanisms and routing and driving the input of particulate wash load to the floodplain are almost unknown, not just for the Amazon River but for almost the totality of the tributaries.

Nevertheless all the significant data presented above, field information with systematic data on Amazon lakes come from the study of the biogeochemical characteristics of a few lakes – in particular from Lake Calado and Lake Camaleão – a fact also enhanced by the classic biogeochemistry and aquatic ecology reviews by Junk (1997) and Melack and Forsberg (2001).

The lack of detailed geomorphologic mapping and the establishment of distinct relations between hydro-geomorphologic and vegetation units, as well as the use of hydrology without considering the dynamic nature of the physical environment, does not allow a better understanding of the hydro-geomorphologic and ecologic behavior of the floodplain and other flooded areas, including lake systems. A multidisciplinary approach strongly based on fluvial geomorphology and detailed hydro-geomorphologic mapping become necessary. Lake morphology and behavior are related to the fluvial regime and to the geomorphologic style of the rivers, as well as to the paleohydrologic landform heritages recorded in the floodplain and lower terraces, which are also related to the floodplain sedimentary architecture.

The Amazon floodplain lakes can be classified as a function of the genetically related fluvial processes, with the following main types:

- (a) Lakes related to lateral channel shifting: lakes in abandoned channels tracts, oxbows (lakes or swamps depending the degree of siltation), composite chained oxbows, scroll bars lakes, composite scroll bars lakes, lakes in lateral accretion processes attaching islands to the floodplain
- (b) Lakes generated by landforms built by vertical accretion processes in the main channel and by floods on the floodplain, affecting the floodplain and tributaries of rivers: round floodplain lakes, lakes generated by floodplain deltas, levee lakes, island levee lakes, blocked valley (Ria Lakes)

Lakes related to lateral channel shifting

Oxbows (lakes or swamps as related to the degree of siltation). Oxbow lakes are typical elements of meandering floodplains. In the Amazon basin, there is a considerable number of tributaries which show meandering patterns, and, in all of them, oxbow lakes are the dominant lacustrine landforms.

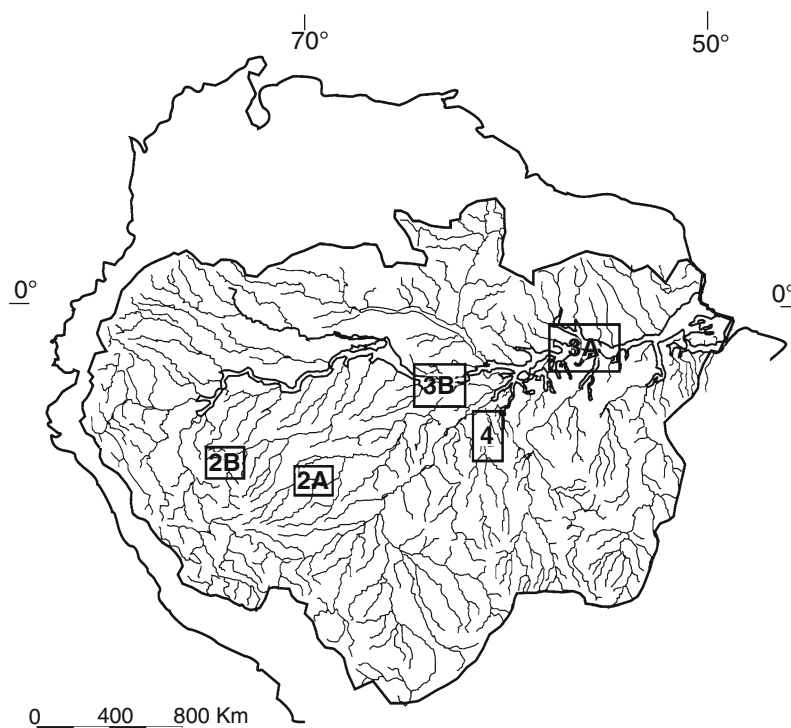
Rivers with abundant sedimentary load draining the lowlands (Jurua, Purus, Javari), as well as mixing terrains

(orogenic areas and lowlands), such as Mamore, Madre de Dios, Beni, Ucayali, Iça, among others, show a variety of meandering patterns. In these rivers, it is possible to identify several generations of abandoned meanders in several stages of siltation in the floodplains and swampy areas, occupying old meanders in the lower Holocene-Late Pleistocene terrace (Figures 1 and 2a). Vegetation is a main indicator to determine the level of evolution/siltation of these lakes.

The typical channel pattern of lowland tropical rivers, such as Jurua and Purus, is that of single sinuous channel with medium to high sinuosity occurring in between shorter straight reaches. The meanders are compounded and asymmetric, and several reaches exhibits irregular and tortuous pattern. Sinuosity in the meandering reaches varies, with values as high as 2.7 and width-depth channel ratio values mostly between 17 and 27. Because of the irregular and tortuous channel pattern, meander geometry shows a wide range of values. Suspended load is dominant, reaching 98% of the total sediment load (Gibbs, 1967; Mertes and Meade, 1985). Meanders are abandoned mainly by neck cutoffs and lateral rates of channel migration are low. Radiocarbon dating in fluvial deposits indicate that during part of the Late Pleistocene (Middle Pleniglacial to early upper Pleniglacial) and Holocene, the lowland rivers suffered important paleohydrological changes, although meandering patterns were always dominant and oxbow lakes a characteristic of these kind of rivers (Latrubesse and Kalicki, 2002; Latrubesse and Rancy, 1998, 2000).

Oxbow lakes are very rare in the Solimões-Amazon main stem and in the Madeira River because of the tendency of the channel to generate an anabranching low sinuosity pattern. However, it is possible to identify a big oxbow lake north of Xibeco which is located on an avulsed fluvial belt of the Solimões main stem (Mertes et al., 1996).

Scroll bar lakes (simple and compounded). These kinds of lakes are generated in between scroll bars, in a meandering scrolled floodplain. The lakes are elongated, usually intermittent and dependent on the flood dynamics. Scroll bars lakes are mainly found in meandering tributaries draining mixed terrains such as the Mamore, Beni, Madre de Dios, Ucayali, and Iça rivers, for example. Compared to the lowland tributaries (Purus, Jurua, Javari), these rivers have more harmonic meanders, show more lateral activity and scrolled floodplains, and transport relatively more bed sandy load. However, scroll bars lakes can also be found in large and complex rivers with tendency to anabranching, such as the Solimões-Amazon. The Upper Solimões have a tendency to anabranching and to generate complex multichannel tracts like the meanders from Iquitos to Tefe (along a reach ~1,100 km in length). The channel-dominated floodplain is a complex mosaic of fluvial forms, including younger channels, active sandbars, islands, levees, scroll-dominated plains, and abandoned belts. The curvature of the scroll morphology suggests that generation by secondary channels or



Amazon lakes, Figure 1 Location map. Numbers indicate the location of the chapter's figures.

paranás are the main factors in the genesis of these deposits and morphologies (Mertes et al., 1996; Latrubesse and Franzinelli, 2002). Specifically, scrolls are mainly generated by lateral activity of the paranás (Figures 1 and 3b). Elongated, narrow and arched lakes occur in the swales. In some places, these lakes may have a finger-like shape, as a result of the ridge and swale topography and the different angles of intersection between the scrolls. With respect to the scrolls, these relate to an upper point bar, and are typically composed of fine sediments.

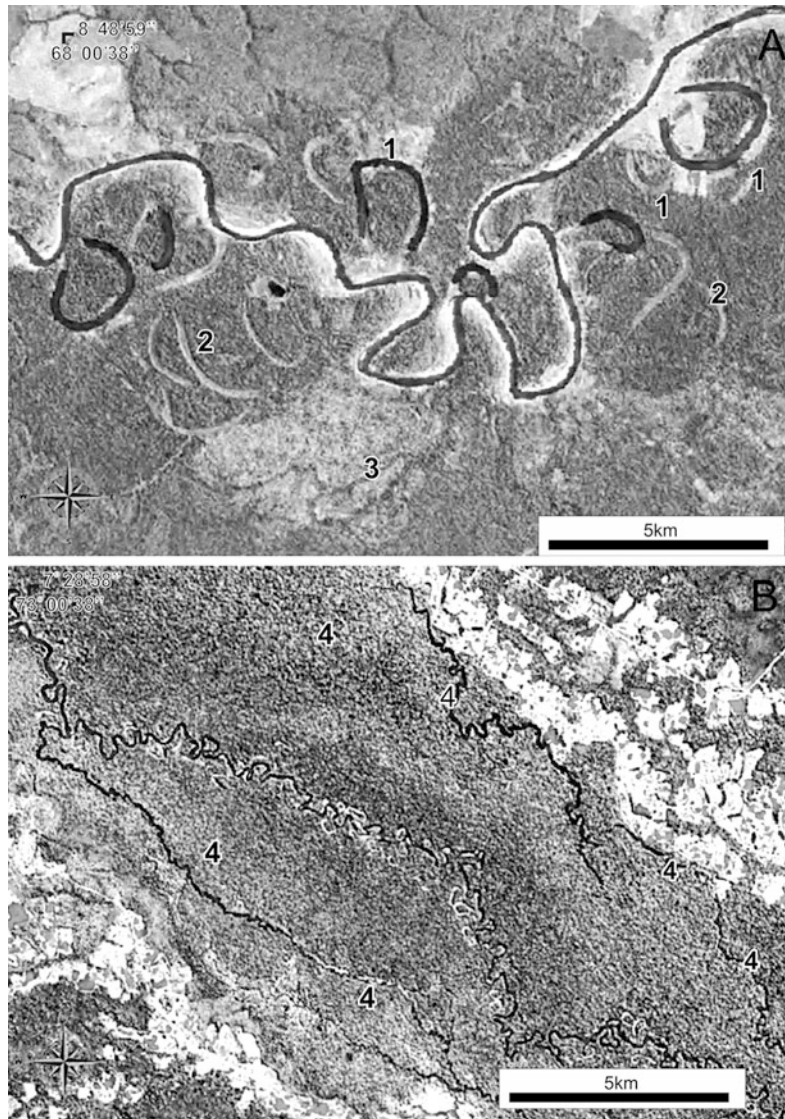
Lakes in abandoned channels tracts. Abandoned channel tracts are associated to avulsion processes, which are particularly related to sunken tectonic blocks or other areas of tectonic instability, as well as to channel instability in flooded basins where rivers shows a tendency to generate vertical accretion floodplains. In the Amazon, these lakes are mainly associated to sunken prismatic tectonic blocks. These “lakes” are in reality a complex relation of pounded areas occupying abandoned channels and floodplain channels connections and, depending on the flood stage, many of them can behave as lakes or have a fluvial tendency to interconnecting and draining away the floodplain. Due to their channel morphology and well-developed banks, these lakes are rather stable in area.

In Brazil, we identified three main areas with this kind of lakes. The first one is located in the lower reaches of the Moa River, a tributary of the Jurua River in the Brazilian southwestern Amazonia (Figures 1 and 2b).

The second area (and good example of a lake developed in abandoned channel) is the confluence between the Japurá and Solimões rivers, where the Reserve of Sustainable Development of Mamirauá is located.

The third one is associated to a sequence of neotectonic blocks affecting the Solimões from Xibeco to the Purus River confluence (Figs. 1 and 3b). Avulsion on the Solimões River, north of Xibeco, has been described by Mertes et al. (1996), while Latrubesse and Franzinelli (2002) found a large abandoned belt of the Solimões River upstream of the confluence with the Purus. At present, the Solimões River flows through the north of this area, close to the northern border of the V-shaped block and near the contact with the upper tertiary Solimões formation. The abandoned belt cuts the previously deposited sediments of the impeded floodplain that currently includes a large number of lakes. It is evident that the Solimões River avulsion caused abandonment of approximately 160 km of the river reach. Radiocarbon dating of the sediments of the Solimões alluvial plain, close to the mouth of the Purus, yielded an age of 1,000 years BP.

In Amazon lowland rivers such as Purus River, older meandering belts abandoned by avulsion were recorded during the early-middle Holocene (Latrubesse and Kalicki, 2002) which indicate that during this aggradation phase, oxbows, as well as lakes in abandoned meandering channel tracts were the main elements of the floodplain. In fact, many of these areas are now occupied by swampy environments.



Amazon lakes, Figure 2 (a) Purus River upstream Boca do Acre city. The tortuous meandering pattern generates oxbow lakes (1). Older swampy areas occupy paleomeanders (2) up to ~7 kyear BP while less spread and shallow swampy areas in old meander scarres (3) can be also founded on the Late Pleistocene terrace (~60–20 kyear BP). (b) Lakes occupying abandoned channels by avulsion in the Moa River floodplain (4). Some of the abandoned channels can be partially and episodically reactivated and fed by floods.

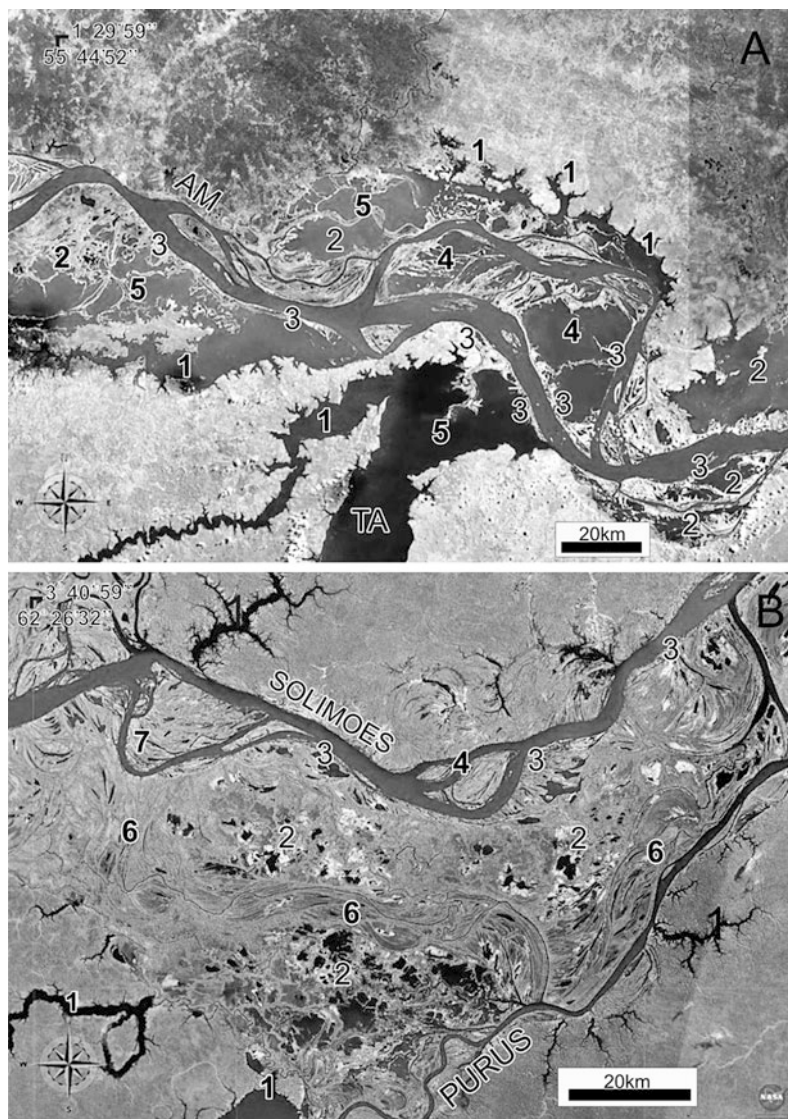
The Ucamara depression in the Peruvian Amazonia can also be used as a good example of lake generation in abandoned channel belts because in this area abandoned meander belts of the Marañón and Ucayali Rivers have been described (Dumont and García, 1991).

Lakes generated by vertical accretion processes in the main channel and by floods on the floodplain (affecting the main river floodplain and tributaries):

These kinds of lakes are generated by flood dynamics mainly in anabranching low sinuosity rivers such as the Solimões-Amazon, the Madeira, and the Japurá (Latrubesse, 2008). The floodplain of these

rivers presents an impeded floodplain alternating with a channel-dominated floodplain as described by Latrubesse and Franzinelli (2002) in the Solimões-Amazon main stem. The impeded floodplain has a complex origin. Its sediments originated in several Holocene temporal stages, but overall, there is a tendency for vertical accretion in this geomorphic unit. Round floodplain lakes, levee lakes, island levee lakes, and lakes generated by floodplain deltas are typical features of this geomorphic unit.

Levee lakes. Large levee complexes lay on the sides of the channels and their development depend on the



Amazon lakes, Figure 3 (a) Amazon river at the confluence with Tapajós River. Note the abundance of blocked valleys (1), rounded lakes in an impeded drainage floodplain (2), the spectacular levees confining the river flow along a narrow corridor inside a water saturated floodplain (3), the large islands and island lakes (4), and delta systems entering in the floodplain lakes (5). (b) Solimões River at the confluence with Purus River. Note the large alluvial belt of the Solimões river abandoned by avulsion (6). The area is located in a neotectonic prismatic block. A large quantity of small rounded lakes form the impeded floodplain unit while secondary more sinuous channels generate small lakes in a scrolled topography (7) and small lakes, mainly temporary, can be founded inside the islands (4). Levees are present (3) and sedimentation of the floodplain blocked several tributaries generating blocked valley lakes (1).

hydraulic geometry of the channel section and channel stability. Low anabranching rivers transporting abundant sedimentary load generate important levee complexes. In the Solimões-Amazon, these complexes increase in importance downstream Manacapuru (Figures 1 and 3a). The height of the levee complex typically varies between 1 and 10 m above the low water level of the river. The sediments characteristically are composed by the intercalation of sandy and fine deposits. Nevertheless, the existence of a sandy platform at the base of the levee is common. The amount of fine sediment and the

intercalation of fine and sandy deposits increase upward and highly bioturbated muddy sediments occur at the upper levels as a consequence of the vegetation colonization of the levee. For example, in the Solimões River at Iranduba, upstream of Manaus, the levee complex is approximately 22 km in length and up to 4 km in width, and the contact between the fluvial sediments and the banks of the Cretaceous sedimentary rocks of the Alter do Chão Formation are visible.

Likewise, levee lakes are also very important features in rivers carrying today a small amount of sedimentary

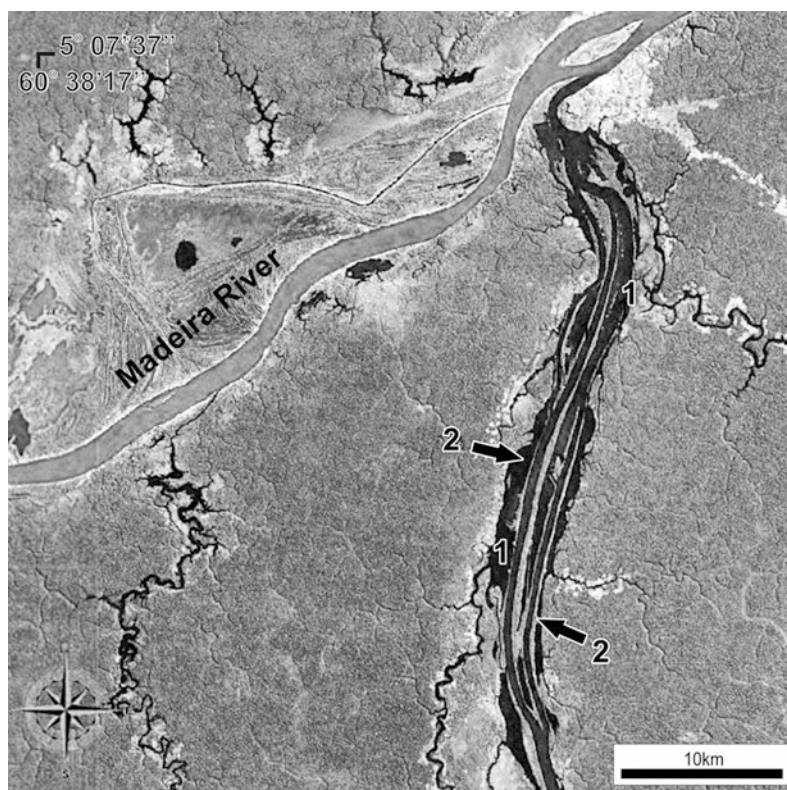
load. As described in the Negro River by Latrubesse and Franzinelli (2005), important paleohydrological changes happened in the Amazon basin during the Late Holocene. Many rivers draining cratonic areas, such as the Negro, the Tapajos, the Xingú, the Trombetas, and the Aripuaná, exhausted their yield of fine sediments, aborting the development of floodplains in recent times. These rivers carry today an insignificant quantity of suspended load and behave as blocked valleys having almost a lacustrine dynamic in their lower reaches. Huge and spectacular levees can be observed inside huge flooded valleys, covered by Igapó forest (Figure 4). In between these levee complexes, lakes, interconnected with the other elements of the floodplain during floods, are present.

Round floodplain lakes and lakes generated by floodplain deltas. Both kinds of lakes are characteristics of the impeded floodplain. As mentioned before, the impeded floodplain is a widespread unit characterized by a number of round or irregularly shaped lakes on a very flat surface, dominated by low sinuosity anabranching rivers such as Solimões-Amazon, Madeira, and Japurá (Figures 3a and b). Some of these lakes are connected to the main system by small channels. Others, however, are isolated from the main channel. At times, this unit is

inundated by annual floods, although it is not totally flooded every year. This unit resembles local flood basins formed by gray to gray-green muddy sediments. Orange or yellow bioturbated mottled sediments are also frequently found, as opposed to primary sedimentary structures. In several places, it is possible to find remnants of tree trunks, some of them in “life” position. In certain circumstances, trunks were associated with strata primarily composed of leaves and stems. Radiocarbon dating of trunks from the basal beds of the Careiro Island, in the Solimões-Amazon River, indicated ages ranging between 300 and 2,500 years (Latrubesse and Franzinelli, 2002; Absy, 1979; Sternberg, 1960).

A conspicuous quantity of round lakes are recorded in the sunken tectonic block of the Solimões River upstream the Purus-Solimões confluence as described before (Figure 3b). The increment in the numbers of lakes was also noticed by (Sippel et al., 1992), who, however, did not identify the cause of this increment which is as a consequence of avulsion activity and channel abandonment of the Solimões River in this area (Figure 3a).

Although the sediments of the impeded floodplain originated in several temporal stages, there is a tendency for vertical accretion in this geomorphic unit. Levees played an important role in alluvial sedimentation. As normally



Amazon lakes, Figure 4 Spectacular levee development in the Aripuaná River, a main Brazilian tributary of Madeira River. The river carries today a very low amount of suspended load and functions as a blocked valley system with a lake dynamic (1) behind the levees (2) which confined the channel.

happens, the distal levee areas consists of more depressed areas that, in some cases, are covered by tropical alluvial plain vegetation. When levees are broken during floods, the distal levee areas become swampy or flooded. Splay-like systems or minor channels develop, connecting the main system with the back-flooded areas. As the splay deltas coalesce with other levees, these depressed areas are constrained and limited, generating lakes.

As expected, these lakes are shallow and their depths correspond to the maximum heights of levees and thickness of the splay deltas. The vegetation (including arboreal physiognomies) frequently covering a flooded area has resulted in several profiles containing large quantities of organic strata at the base of the sedimentary column. Organic strata are formed by detritus such as stems and leaves marking the original soil/substrate of the newly generated lake or flooded area. While low energy sedimentation is in process, the dead flooded trees are buried in a vertical position.

Additionally, recent sediment of the present-day channel occurs locally on the impeded floodplain, indicating that the modern alluvial system is actively blanketing and reworking the impeded floodplain deposits.

Island levee lakes. The islands in large anabranching low-sinuosity rivers such as the Solimões-Amazon and the Madeira usually have a “sandy core” formed by sandy bar deposits (Figures 3a and b). The creation of an island includes two distinct processes: (1) the generation of a sandy bar or sandy core of the island (on – or without – a “skeletal base” of impeded floodplain deposits), and (2) a mix of vertical and lateral accretion processes associated with main channel dynamics. However, in some cases, the base of the impeded floodplain is not found, resulting in a base composed of channel sandy bar. The typical evolution of an island begins with the development of large channel bars mentioned above. These sandy units are then stabilized by pioneer vegetation. The original bar takes a hexagonal shape. At a later stage, levees begin to develop and to characterize the mix of vertical and lateral accretion stage of the island. The vertical accretion processes build an emerging area frequently flooded during the annual floods. The island surface presents a ridge-and-swale topography similar to that of the scroll-dominated floodplain, but with straighter scroll morphologies. The upstream ends of the islands have abrupt erosive banks up to several meters high during low water level. On the other hand, the low sinuosity of the main channel favors the development of low sinuosity scroll/levee morphologies. Thus, an undulated landscape with a straight ridge-and-swale topography develops on the island surface. A few small elongated lakes persist in the swales in which fine sediments are deposited until the lakes become filled. Because of the smoothing of the older core ridges in the island, a large “inland” rounded to digitate lake can appear in the core of the islands. Lake Camaleão, a systematically studied lake of the Amazon floodplain, is a good example of an island levee lake.

The persistency through time of this kind of lakes varies in each fluvial system or fluvial track. For example, ^{14}C dating of sediments in the large Careiro Island (ca. 415 km²) which contains lake Rei indicates that the island was almost a continuous channel feature for more than 2 kyear (Sternberg, 1960; Absy, 1979; Latrubesse and Franzinelli, 2002).

Blocked valley (Ria lakes). Blocked valleys are characteristic of the Amazon basin and probably in no other fluvial basin of the world this kind of geomorphic features are more spectacular than here (Figures 3a and b).

Blocked valleys or “ria lakes” were interpreted to be formed when valleys scoured during periods of lowered sea levels of the Late Pleistocene related to a sea level ~100 lower than today which were subsequently flooded during the Holocene (Sioli, 1984; Irion, 1984; Irion et al., 1997) or related to tectonic effect in prismatic sunken blocks (Dumont, 1993; Iriondo, 1982) but in concrete they are related to the difference in sediment transport and energy between a main system carrying abundant sedimentary load developing a significant floodplain blocking the mouth of a tributary which has a lower energy and a lower sediment discharge than the collector system. The eustatic effect is not necessary to develop this kind of lakes. Because of the low slope that characterize large rivers, adjustments in the longitudinal profile as response to eustatic changes are just transmitted some hundreds of kilometers upstream from the river mouth. In the Amazon River water slope is extremely low, oscillating from ~6 to 3 cm/km and blocked valleys are recorded in regions that were without direct effect of sea-level changes. Blocked valleys are founded very far from the ocean, in areas which were not affected by sea-level changes such as the Ucamara depression in Perú, the upper floodplain of the Araguaia River (tributary of the Tocantins), and others.

Additionally we need to take account that the sea level was changing along the glacial cycle and not permanently located to 100 m below present sea level. In this case the adjustments along the longitudinal profile were dynamics and would not be only related to the lowermost level reached by the marine regression as claimed by Sioli (1984) and others when comparing the ~100 m depth channels of the Amazon or the ~80 m of the Negro river near Manaus.

Lakes in blocked valleys have “clear” and “black” waters because the production of sediments of the blocked tributaries basins covered by rainforest is very low.

Other big rivers where almost blocked by the Solimões-Amazon as well. For example the lower Negro was partially blocked by the Xiborema levee complex but the huge discharge of the Negro which is constrained by geologic effect in the lower reach permit that the river reaches the Solimões (Latrubesse and Franzinelli, 2005). The Tapajos River, which has less discharge than the Negro, suffered strongly the blocking effect because of the development of a very stable levee complex on the right side of the Amazonas River. The huge Tapajos valley is flooded

and the river connects to the Amazon by a small and narrow mouth. Sediments of the Amazon transfer behind the levee, as described for delta lakes entering the water saturated floodplain, with the only difference that here they enter in a huge blocked fluvial system, the Tapajos, forming a delta system as earlier described by Sioli (1957, 1984). Because ria lakes are in fact blocked fluvial valleys, w/d ratios are in relation to the original morphometry of the former fluvial channel and floodplain. Depth can be significant and may reach more than 10 m in some systems along the original thalweg of the former channel. The Lake Calado close to Manacapuru is the most limnologically studied blocked valley lake. As hydro-geomorphologically expected in these kinds of lakes, limnological studies identified that the Calado water level oscillates near 10 m and local runoff, direct rainfall and seepage are responsible for ~78% of the water input (black water) while contributions from the Amazon River floods are not significant and restricted to the “confluence” zone of the tributary ria lake with the Amazonas floodplain (Lesack and Melack, 1995).

Reservoirs in the Amazon basin

Near 93% of the electric power of Brazil is generated by over 400 large and medium-size power dams. In the Amazon basin, dams are concentrated in the Brazilian territory (Table 2), with two large reservoirs located in the Amazon fluvial basin: Balbina, built on the Uatuma River in 1987 to supply power to Manaus, and Samuel, also built on a relatively small size river, the Jamarí, a tributary of the Madeira River. Balbina has flooded 2,400 km² of rainforest to produce 250 MW, enough for only half of the city's present needs. Balbina is a good example of an engineering and environmental disaster because of the large impacts and the small hydropower production.

Other dams built in the Amazon rainforest during the last decades are in the Tocantins River basin. This basin has experienced a huge human pressure during the last decades since the construction of Tucuruí dam and the expansion of the agricultural and cattle ranch frontier along the savannas (Cerrado) of Central Brazil and the

development of the Tocantins State. The Tucuruí Hydropower Complex, completed in 1984 in the lower Tocantins River, was the first large dam built in the Amazon rainforest for hydropower generation but today six large dams exist on the Tocantins River.

The role of large dams in the generation of green house gases (carbon dioxide and methane) is remarkable. Estimates of emissions during the first decade after reservoir filling for the year 1990 (i.e., the baseline year for national greenhouse gas inventories under the climate convention) totaled ten million tons of carbon for the existing dams in Brazilian Amazonia: 2.55 at Tucuruí, 6.43 at Balbina, 1.13 at Samuel, and 0.01 at Curuá-Una while methane emissions should be 90,000 t and 140,000 t in Tucuruí and Balbina, respectively (Fearnside, 1995).

Feasibility studies are currently being carried out on the Xingu, Madeira, Tapajós, Teles Pires, Trombetas, and Araguaia rivers in the rainforest environment and the Amazon-Cerrado ecotones. Without exception, all the related projects are marked by severe social, economical, and environmental controversies.

Particularly controversial are the dams in the Madeira and Xingú rivers.

With 32,000 m³/s of mean annual discharge, the Madeira is the fourth largest river of the world in water discharge and the most important tributary of the Amazon. The Upper Madeira developed some of the world's most spectacular sequence of rapids between Porto Velho and Guajará Mirim (Figure 5).

Two hydroelectric dams currently under construction are Jirau and Santo Antonio, on an uneven stretch of the upper Madeira River, in the western Brazilian State of Rondonia. These complexes, part of a larger four-dam cascade to generate electricity and permit navigation along the Peruvian and Bolivian tributaries, could have a potential energy production of 3,300 and 3,150 MW, respectively, and a cost of approximately 12\$ billions. To provide a scale of the significance of this system, we can mention that at the dammed area, the Madeira River transports more water discharge than that originally transported by the Yangtze River at the largest dam of the world: Three Gorges.

Amazon lakes, Table 2 General data of the main dams of the Brazilian Amazon basin

Dam	Latitude	River	Year of construction	Biome	Power (MW)	Reservoir area (Km ²)	Estimated cost
Tucuruí	03°45'S; 49°40'W	Tocantins	1984	Rain forest	4,240	2,430	US\$5.5 billions
Samuel	08°45'S; 63°28'W	Jamari	1988	Rain forest	217	645	US\$836 millions
Balbina	2°26'24" S; 58°15'0" W	Uatuma	1987	Rain forest	218 planned but 112.2 produced	2360	US\$1000 millions (estimated)
Curuá Una	2°50'S; 54°18'W	Curuá Una	1977	Rain forest	40	72	–
Santo Antonio and Jirau	8°49'; 63 58 and 9°19'S; 64°43'W	Madeira	Under construction	Rain forest	3,150 and 3,300 respectively	271 and 278 respectively	US\$12 billions
Belo Monte	3°26'S; 51°36'W	Xingú	Put out to tender	Rain forest	11,000	516	US\$11 billions



Amazon lakes, Figure 5 Teotônio Rapids, located in the area of influence of the Madeira's dams, upstream Porto Velho city. The Madeira generated at these reach the largest rapids of the world in terms of water discharge. This sequence of spectacular rapids (Jirau, Teotônio, Santo Antonio) will disappear because of the dam's construction.

From a hydro-geomorphologic point of view, the Madeira River offers a tremendous challenge for river management and dam building because of the inexistence of gorges or abrupt relief. The river valley cuts a low landscape and a lower terrace and at this reach the mean annual discharge is more than 22,000 m³/s with peaks that reach more than 80,000 m³/s. The suspended sediment transport is ~280 Mt (Filizola and Guyot, 2009). Because of the insignificant relief, mistakes in the project can produce huge environmental impacts due to the permanent flooding of the lower terrace, generating swamps in both sides of the river (in Bolivian and Brazilian territory), as well as affecting the longitudinal profile of the tributaries, what would transmit environmental impacts to their floodplains. The decline of sediment availability downstream the dams and high environmental impact in the lower Madeira and lower Amazon system are expected.

In the Xingu River, Belo Monte dam, first proposed in 1975 by Eletronorte (a state-owned utility company) and originally consisting of two dams (Babaquara and Kararaô), is one of the recurrent projects proposed for hydropower generation since the 1970s.

The whole complex would have five generating plants along the Xingu River with the capacity to generate 14,700 MW (Fearnside, 1995). In fact, Eletronorte suggested to build up to four additional dams (Altamira, Ipixuna, Krokaimoro, and Jarina), flooding a total area of 22,000 km² (Fearnside, 1995, 2005).

Recently, the project was reevaluated and redesigned for a reservoir area of 440 km² (Carvalho, 2006) and an installed capacity of 11,181 MW. The estimative cost of the reservoir would be at least \$12 to \$18 billions. However, the Altamira/Babaquara Dam which should be located upstream to increase the power generation at Belo Monte would flood an area of 6140 km² (Fearnside, 2006).

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Cross-references

[South America, Lakes Review](#)

ANTARCTIC LAKES

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Antarctica

The Antarctic continent, including its ice shelves, has an area of 13.8 million km², about half the size of North America and 1.3 times the size of Europe. It is also the highest, windiest, coldest, and driest of the continents. Almost the entire land surface of Antarctica is covered by a vast ice cap, with an area more than six times larger than its counterpart in Greenland. In places, the ice cap is 4 km thick. Here, summer temperatures rarely get above –20°C and monthly means fall below –60°C in winter. Vostok station, at 78°South holds the record for the lowest ever temperature recorded at the surface of the Earth (–89.5°C). On the coasts of Antarctica temperatures are generally close to freezing in the summer months (December–February), or even slightly positive, particularly in the northern part of the Antarctic Peninsula. During winter, monthly mean temperatures at coastal stations are generally between –10°C and –30°C, but may briefly rise toward freezing when winter storms bring warm air toward the Antarctic coast. With average precipitation (as snow) amounting to only 100–150 mm of water equivalent a year the area is technically a desert, although

the ice cap contains almost 70% of the world's freshwater and 90% of the world's ice. The surrounding ocean freezes in winter to cover an area 1.5 times the size of the continent.

Only 0.32% of the Antarctic continent is ice-free. This mainly consists of mountain peaks (nunataks) protruding from the polar ice cap. However, 1–2% of this includes coastal oases that have been exposed, both through postglacial retreat of the ice cap and isostatic rebound of the Earth's crust following the most recent deglaciation. The largest oasis is situated near the coast of the Ross Sea and is known as the McMurdo Dry Valleys. Other large oases are found in eastern Antarctica including the Vestfold Hills, Larsemann Hills, Bunger Hills, Schirmacher Oasis, Syowa Oasis, and on the Antarctic Peninsula at Ablation Point on the east coast of Alexander Island. There are also numerous islands surrounding the Antarctic continent south of 60°S. Most lie close offshore but a few form discrete archipelagos 100–500 km from the mainland (e.g., South Shetland Islands and South Orkney Islands), some are active volcanoes (e.g., Deception Island, Ross Island, and the South Sandwich Islands) while others are isolated, far out in the Southern Ocean (e.g., Macquarie Island, Heard Island, and Amsterdam Island). Collectively the ice-free coastal oases of the continent and the ice-free ground on the islands support much of the well-known fauna of seals, penguins, and marine birds, as well as a variety of macro flora including higher plants, mosses and lichens.

Antarctic lake types

Given the limited area of ice-free ground, it is perhaps surprising that the Antarctic continent and subantarctic islands (loosely defined as those areas south of 60°S latitude) are home to one of the most diverse and interesting lake districts on Earth. Indeed, even though the Antarctic is the repository of more than 70% of the world's freshwater, less of it is available in liquid form than on any other continent. Nevertheless, water bodies that contain liquid water for at least part of the year are a common feature of the Antarctic landscape. This is because water accumulates in areas where solar radiation and advected heat promote melting. This process is self-perpetuating since, as bare ground is exposed, its albedo drops and more radiation is absorbed. As a result, liquid water is not uncommon on ice-free ground. However, liquid water also occurs on and beneath the glaciers and ice sheet. Wherever this water accumulates lakes and ponds are formed. Below we describe some of the different lake types found in Antarctica.

Lakes in ice-free areas

Among the most intensively studied Antarctic lakes are those that occur in the ice-free oases on the edge of the continent such as the Vestfold Hills, Larsemann Hills, and McMurdo Dry Valleys, and those on the maritime and subantarctic islands such as Signy Island and King

George Island. These range in size from small ponds to lakes of $>10 \text{ km}^2$, in depth from few mm to over 300 m, and in age from a single summer to several full glacial cycles. Those that contain liquid water throughout the year, with either seasonal or perennial ice insulating the water against heat loss and complete freezing, are generally referred to as lakes while those that freeze to the base during winter (typically $<2 \text{ m}$ deep) are referred to as ponds. Most of these lakes postdate the Last Glacial Maximum, between 25,000 and 18,000 years ago, when the ice sheet expanded over many of the coastal oases and across the continental shelf. As this ice receded it exposed depressions in the landscape, formed either from glacial erosion or the deposition of terminal moraines, or as a result of folds and depressions in the underlying geology. These depressions filled with water, the lakes were colonized by a range of organisms, and began to accumulate the sediments that today reveal their history. In some rare areas lakes survived intact through the Last Glacial Maximum, for example, the Larsemann Hills, Schirmacher Oasis, and Bunger Hills; and in the McMurdo Dry Valleys, lakes have occupied some of the valley floors in different configurations for over 300,000 years, their depth and area being determined by the spatial extent and thickness of bounding ice sheets and glaciers. Lakes on the subantarctic and peri-antarctic islands are often of Holocene age, formed during the retreat of local ice masses and cirque glaciers. Some of the islands further north such as Macquarie Island may have escaped extensive glaciation and are likely to contain older lakes.

Many of the lakes at lower altitudes in ice-free areas are below the Holocene marine limit ($<40 \text{ m}$ in the Antarctic Peninsula, $<8 \text{ m}$ in the Larsemann Hills) and have formed in depressions emerging from the sea as a result of postglacial isostatic rebound (Figure 1a). Conversely, those at higher altitudes and above the Holocene marine limit have had no prior hydrological contact with the ocean. Where the lakes have no surface outflow they are referred to as closed (or endorheic) lakes. Some of these closed lakes have subsequently experienced an excess of evaporation over precipitation and have gradually become saline. Examples of these are found in the Rauer Islands (Figure 1b), Vestfold Hills, Windmill Islands, and McMurdo Dry Valleys. Some saline lakes become stratified for part of the year (monimictic) and others are permanently stratified (meromictic), retaining a trapped layer of salt water below their fresh surface waters. Lakes that have outflow streams are classified as open lakes; these are typically freshwater and do not accumulate salts to the same degree. Both types of lake are common in Antarctic oases such as the Larsemann Hills, Vestfold Hills, Schirmacher Oasis, Bunger Hills, and on the Antarctic Peninsula (Figure 1c) and maritime antarctic islands.

Epishelf lakes are formed in marine embayments or fjords, dammed by advancing glaciers and ice shelves and have been described in the Bunger Hills, Schirmacher

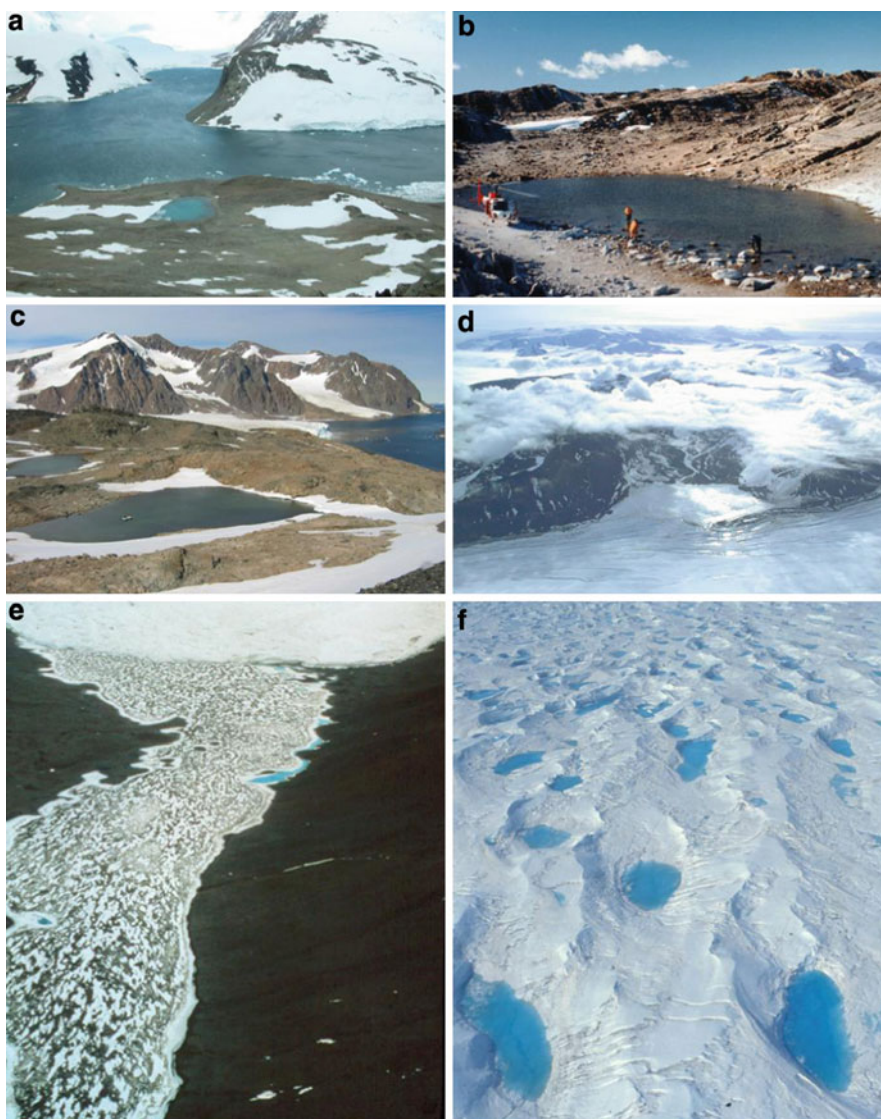
Oasis, Amery Oasis, and Antarctic Peninsula. In these lakes the marine water is replaced over a period of time by fresh melt water from glaciers and snow. In some cases the bounding ice forms an incomplete seal and a hydraulic connection to the sea persists under the ice shelf or glacier, sometimes more than 100 m below sea level. When this happens the epishelf lake becomes stratified with freshwater overlying a layer of dense saline water. Where the seawater flows freely under the ice shelf or glacier a tidal regime can be maintained, which is revealed at the surface by, often characteristic, tide cracks that appear in the ice around the edges of the lakes. Two examples of tidal epishelf lakes are found on the coast of Alexander Island (Moutonnée Lake (Figure 1d) and Ablation Lake). Other epishelf lakes are currently isolated from the sea, formed during earlier periods of relative sea-level rise, lifting grounded ice masses and allowing sea water to penetrate into the lower part of the water column, or connected to marine waters only during periods of reduced freshwater input.

Lakes beside, on, and under the ice

Liquid water is also found against glacier fronts or beside ice shelves, in depressions on glaciers, ice sheets, and ice shelves, and beneath the Antarctic ice sheet. These are called epiglacial, supraglacial, and subglacial lakes, respectively.

Epiglacial lakes are usually formed in depressions at the boundary between areas of rock and ice and are often perennially ice-covered. They are found around the edges of Antarctic nunataks, at the snouts of glaciers, and along the grounded edges of glaciers and ice shelves. They are among the most common lake types in Antarctica and can be found deep in the interior of the continent to within a few hundred kilometers of the pole. Along the Antarctic Peninsula and on the subantarctic islands the lakes are often ice-free in summer with snowmelt from the rock catchment, and meltwater from the bounding ice both contributing to the standing body of liquid water. Although mainly seasonal, epiglacial lakes may persist for several years, often with frequent changes in water level and morphology on account of glacial movements and changing meltwater inputs. Some, such as Lake Untersee in East Antarctica, are older than 500 years. Further south, they can be permanently ice covered with occasional moats forming as a result of advected heat on the landward sides melting the lake ice during warmer summers. This glacial meltwater can also occasionally flood the surface and refreeze restoring the “flat” surface of the lake as seen at Edge Lake in Davis Valley in the Dufek Massif. Some of the largest epiglacial lakes are found at glacier fronts in the McMurdo Dry Valleys (e.g., Lake Fryxell and Lake Hoare, Figure 1e).

Supraglacial lakes are found on the surface of the ice sheet, glaciers, and ice shelves and range from cryoconite holes, less than a meter across, to meltwater lakes that can extend to several square kilometers. They are typically seasonal, forming during the summer melt (Figure 1f).



Antarctic Lakes, Figure 1 Photographs showing selected Antarctic lake types, (a) an isostatically uplifted “isolation basin” lake on Pourquoi-Pas Island, Antarctic Peninsula (in the foreground), (b) a hypersaline closed basin lake in the Rauer Islands, East Antarctica, (c) an open basin freshwater lake on Horseshoe Island, Antarctic Peninsula (d) Moutonnée Lake – an epishelf lake on Alexander Island, formerly a marine basin, now a stratified lake impounded by George VI ice shelf (in the foreground), (e) epiglacial Lake Hoare in the McMurdo Dry Valleys, and (f) ephemeral supraglacial lakes on the Sörsdal Glacier in the Vestfold Hills, East Antarctica, each of these lakes is approx. 250 m wide.

The larger meltwater lakes occupy depressions formed by the stress of moving ice and areas that will later become crevasses. Cryoconite holes are small cylindrical depressions in the ice, likely formed by the presence of wind-blown material including mineral sediments and desiccated microbial mat that provide small concentrations of advected heat sufficient to melt down into the ice. The subsequent growth of microbial mats in these depressions can often serve to enhance this process and so a more-or less self-maintaining ecosystem is formed containing liquid water and supporting a surprising diversity of

biological communities. It is not surprising, therefore, that they have been proposed as one of the main refugia for the eukaryotic biota in the controversial Snowball Earth hypothesis, when the Earth underwent extreme freeze-drying events between 750 million and 580 Ma ago. Kettle ponds can also form in depressions on ice-cored moraines where the rock promotes the melting of ice through reduced albedo and advected heat. Many of these contain diverse and productive biological communities, the most well-known examples being found on the surface of the McMurdo Ice Shelf at Bratina Island.

Subglacial lakes, rivers and wetlands, deep beneath the Antarctic ice cap were revealed by airborne radio echo sounding in the 1970s. These lakes, which lie up to 4,200 m under the Antarctic ice sheet, range in size from 1 km to 241 km long. The largest and deepest of these is Lake Vostok. This lake covers an area of 14,000 km² (about the same size as Lake Ontario, Canada), has a mean depth of 150 m, and a water residence time estimated to be around 50,000 years. Others are found in the Dome C and Ridge B regions of eastern Antarctica (Siebert et al., 2001). To date the subglacial lakes in Antarctica have remained unexplored except using remote technology. The intriguing question is what these subglacial lakes are likely to contain biologically, and what their accumulated sediments might reveal about the history of the ice sheet. In terms of life, the evidence to date suggests that scientists might discover communities of microorganisms, as the ice core extracted from above Lake Vostok has revealed a diversity of yeasts, Actinomycetes, algae, and spore-forming bacteria. Some of these organisms have remained viable in the ice for 36,000 years. Since the ice above Lake Vostok is over 500,000 years old, there is speculation that the lake will contain microbial genomes which have been isolated from the rest of the biological world for that period. The prospect of analyzing these subglacial communities, their genetics and physiology might open up a wide variety of questions concerning Antarctic biogeography and microbial evolution (Doran et al., 2004).

Physical, chemical, and biological features of the lakes

Physically, the lakes experience low temperatures (<10°C) and have varying degrees of ice cover usually between 1.5 and 6 m thick during winter. Some ice cover is permanent (perennial) while in other lakes increased summer temperatures can cause the ice to melt completely, or peripherally forming moats. The ice forms a thermal barrier that prevents most lakes from freezing to the bottom. Nevertheless, a minority of shallow lakes are not sufficiently protected from the wind and can freeze to the bottom such as Lake Ferris in the Larsemann Hills, or freeze to within a few centimeters of the bottom where the ice overlies a thin layer of hypersaline brine such as Lake Vida in the McMurdo Dry Valleys and Forlidas Pond in the Dufek Massif. These are known as dry-based lakes. Other lakes are ice-free or nearly ice-free all year round on account of hypersalinity, examples being Deep Lake in the Vestfold Hills, Don Juan Pond in the McMurdo Dry Valleys, and some lakes in the Rauer Islands. Ice and snow cover results in low levels of annual photosynthetically available radiation in the lakes. However, when the ice melts in summer, the high transparency of the water column can transmit so much light that it has an inhibiting effect on photosynthesis.

Chemically, the lakes range from some of the freshest lakes in the world to hypersaline lakes with concentrations of salt exceeding eight times that of seawater, preventing

them from freezing over, even during winter when their water column temperatures can drop below -10°C. Many saline lakes exhibit seasonal or permanent stratification of their water columns due to temperature and salinity gradients. Epishelf lakes such as Kakapon Bay in the Bunger Hills can exhibit full marine conditions together with a marine flora and fauna including seal populations. Others, like Moutonnée Lake on Alexander Island, have marine water restricted to the lower parts of the water column. Depending on the degree of chemical influence from the sea, versus interior climate regimes, lakes are often classified as “coastal maritime” or “coastal continental.” The nutrient status of Antarctic lakes is typically oligotrophic, with eutrophy usually restricted to those which are directly influenced by visiting marine mammals, birds, or people.

Biologically the lakes contain few zooplankton and no fish. Mosses are the highest forms of aquatic plant life on the continent, while higher plants and some emergent vegetation are present in lakes on the peri-antarctic and sub-Antarctic islands (e.g., South Georgia). Phytoplankton and bacterioplankton populations are present in most lakes and experience large seasonal variations in their populations, often related to the light climate. However, the bulk of the biomass and primary productivity is benthic, consisting of cyanobacteria, diatoms, and green algae, often in luxuriant mats several meters thick (Vincent, 2000; Ellis-Evans, 1996). The mats can be grazed by communities of rotifers, ciliates, and crustacea, though usually these zooplankton are present at low densities. Benthic microbial mats are less common in the saline lakes, but even the most saline ones contain some biota. Other biological habitats include pockets within the lake ice, the under surface of the lake ice, and the micro stratified chemoclines of meromictic lakes where gradients of conductivity, oxygen, pH, and sulfur provide numerous niches for photosynthetic sulfur bacteria, other anoxic bacteria, and methanogenic Archaea.

The biological communities of Antarctic lakes utilize truncated food chains characterized by the microbial loop (Laybourn-Parry, 1997) in which heterotrophic and phototrophic bacteria and small eukaryotic phytoplankton are consumed by heterotrophic nanoflagellates (HNAN), which are themselves consumed by larger protozoa and then metazoa, linking the energy lost as dissolved organic matter (DOM) back (loop) to zooplankton and other consumers of net plankton. DOM can enter the pelagic environment from a variety of sources: excretion of dissolved organic carbon (DOC) by algal cells, algal cell lysis by inefficient grazing by mesozooplankton, or diffusion from fecal pellets. The food web is therefore driven by recycled carbon.

Despite a biological composition that is primarily microbial, what the Antarctic lake biota lacks in size, is more than makes up for in biomass and species diversity; both considerably greater than that found in adjacent Antarctic terrestrial environments (Vincent, 2000). In fact, with many higher organisms unable to survive there, the

Antarctic continent could be seen as a microbial world with the lakes being its principal bastion. A recent study of the species composition of benthic microbial mats from selected lakes in the Larsemann Hills, Vestfold Hills, and McMurdo Dry Valleys found 1500 strains of bacteria (in a subset of 9 lakes), 60 strains of cyanobacteria (24 lakes), 230 strains of fungi (17 lakes), 91 strains of algae (3 lakes), and 50 protozoans (6 lakes). These were identified using combinations of morphology, phenotypic, chemotaxonomic, and molecular taxonomy. For bacteria, 320 clones were obtained from a single mat sample that would fit into a teaspoon! Technological advances have enabled scientists to study species compositions ranging from aerobes to anaerobes, from primary producers to degraders and brought a new level of detail to understanding of Antarctic lake food-web ecology.

The origin of the biota in Antarctic lakes

With this remarkable diversity of life present in Antarctic lakes, there has been an ongoing debate on its origins (see Gibson et al., 2006 for an authoritative account). The key question is whether the biota are primarily postglacial colonists, arriving through dispersal from sub-Antarctic islands and more northerly continents (e.g., South America) that had remained ice-free, or whether they are vicariant, surviving glacial advances in lacustrine refuges, and then recolonizing newly deglaciated areas. The latter model allows for a greater degree of endemism and the possibility that Antarctic lakes could contain species that are relicts of Gondwana.

Recent field data has provided the first hard evidence of zooplankton that have survived an entire glacial cycle. Thus, it is likely that non-glaciated lakes, epiglacial lakes, and cryoconite holes, for example, have provided refugia for many of the species found in Antarctic lakes, during past glacial cycles. There is also evidence of species that have become extinct in particular environments during glaciation and species that have dispersed to the Antarctic in the present interglacial from the maritime and sub-Antarctic islands and from the other higher latitude continents of the southern hemisphere (South America, Australasia). The different groups that comprise the vicariant species and the colonizers are usually differentiated by their life history, in particular the presence or absence of a life history stage capable of dispersal across the formidable barriers of the polar frontal zone and the circumpolar winds of the Southern Ocean.

Antarctic paleolimnology

Many Antarctic lakes accumulate sediment deposits that incorporate the products of glacial erosion together with biological and chemical fossils. These inorganic, biological, and chemical deposits respond rapidly to changes in temperature, precipitation, evaporation, light environment, ice cover, and glacial extent. Thus, lake sediments

can document both the lake's development and changes in the surrounding environment and have proved invaluable not only in determining the lakes' histories but also in addressing some major questions in Earth system science (Hodgson et al. 2004). For example, the onset of sedimentation in lake basins has provided data on the extent and timing of glaciation and deglaciation and environmental change. Lakes situated below the Holocene marine limit that have been isolated from the sea contain a record of the isolation event and this can be dated using radiocarbon technologies. From this it is possible to construct a history of marine transgressions and hence the relationship between relative sea-level change, ice thickness, global eustatic sea-level change, and isostatic rebound. Such data are enabling ice sheet modelers to accurately reconstruct the past, and better predict the future, contribution of Antarctic ice to global sea-level change. This is a pressing task as predicted increases in global temperature over the coming decades threaten the stability of some parts of the Antarctic ice sheet which, in total, has sufficient ice to raise global sea levels by as much as 70 m. Although this volume is highly unlikely to melt, evidence from the last interglacial, which was only very slightly warmer than our own (1–2°C), shows that global sea levels were 5 m higher than they are today and it is likely that high latitude ice reservoirs provided the source.

Epishelf lakes are also yielding valuable paleolimnological information on the ice shelves and glaciers that impound them. For example, sediments from Moutonnée Lake on Alexander Island have revealed that the currently extant George VI Ice Shelf broke up in the early Holocene, following a period of atmospheric warmth and at the same time as an intrusion of warm water under the shelf. The history of ice shelves is important as ice shelves help restrain the glaciers that flow into them, on account of being pinned to submerged rises in the ocean floor. Without the restraining ice shelves it is proposed that the inland ice of Antarctica could flow at an accelerated rate into the ocean and thereby increase the Antarctic contribution to global sea-level rise.

Paleolimnological studies have also tracked changes in lake salinity from which the atmospheric moisture budget can be inferred and compared with the evidence from Antarctic ice cores. Other studies have tracked the origin and development of the lake biota and, from this, made inferences about the nature and direction of environmental change.

Despite clear signs of marked recent environmental changes in the Antarctic we, as yet, have only a limited perspective on how Antarctic climates and environmental conditions have varied in the past. As long-term monitoring programs in high-latitude regions have only been established for the past several decades, paleolimnological methods will continue to have a role in developing our understanding past environmental changes and helping us to anticipate the magnitude, nature, and direction of future change.

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ANTARCTIC SUBGLACIAL LAKE ELLSWORTH

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Introduction

Subglacial Lake Ellsworth is located near the Ellsworth Mountains in West Antarctica at 78.9°S 90.6°W. The lake basin is in the center of the West Antarctic Ice Sheet (WAIS) in the Pine Island Glacier drainage basin, 20 km from the ice divide with the Institute Ice Stream. The lake is believed to be approximately 10 km long and over 3 km across at its widest point. The gradient of the bed surrounding Lake Ellsworth is at least twice as great as the lake surface, which implies that the depth of the lake could be of the order of tens if not hundreds of meters (Siebert et al., 2004). The ice overlying the lake is between 3.2 and 3.4 km thick, suggesting that the lake surface

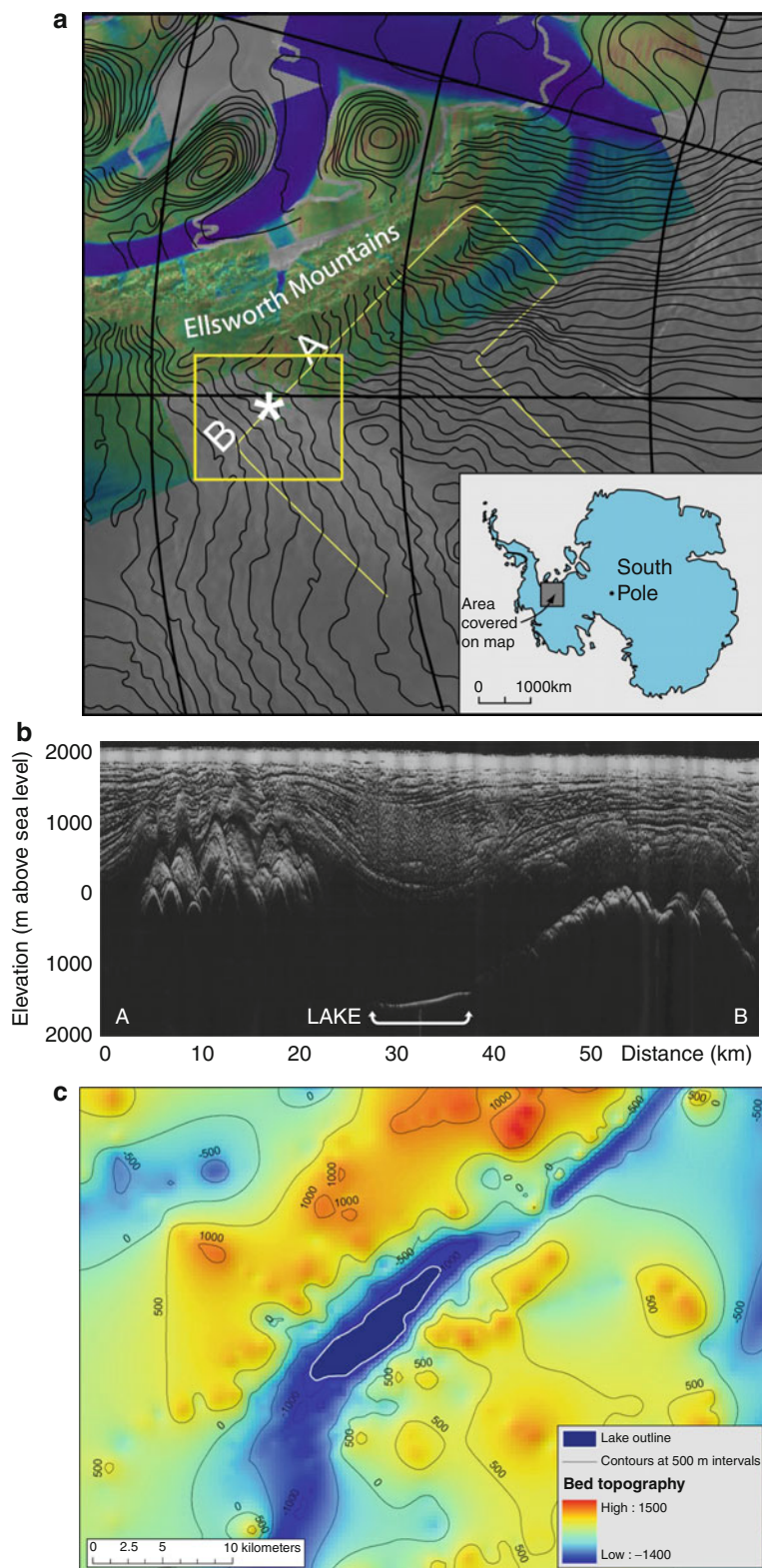
is over 1 km beneath present sea level. Lake Ellsworth is located within a distinct topographic hollow, which is ~1.5 km deeper than the surrounding bed. The basin is fjord like in its topographic setting, and is one of a series of fjord-like over-deepening on the western flank of the Ellsworth Subglacial Highlands.

This summary of Lake Ellsworth will first document the series of radio-echo sounding (RES) transects from which the lake has been identified. Basal thermal regime and ice flow conditions which are believed to control the lake will then be described. The final section will describe future plans for the exploration of Lake Ellsworth (Lake Ellsworth Consortium, 2007).

Radio-echo sounding data

Subglacial lakes can be identified on RES records (see entry for “*Antarctic Subglacial Lakes*”). Two independent airborne and one ground-based RES campaigns have identified Lake Ellsworth:

1. The first knowledge of Lake Ellsworth is reported in Siebert et al. (2004), and is restricted to one RES line, acquired in 1977–1978 (Figure 1). Later RES profiles (described below) suggest that the sounding line is near parallel to the lake’s long axis, and is also near parallel to ice flow over the lake. This fortuitous occurrence is ideal for modeling the lake environments. The mean gradient of the lake surface reflector is 0.02, about ~11 times the ice surface slope, suggesting the lake is in hydrostatic equilibrium with the overriding ice. The slope of the ice base across Lake Ellsworth is not entirely constant; being concave over the lake’s upstream side and convex across its downstream side. In other words, the ice sheet “sags” as it flows onto the lake, and buckles against the sidewall as it regrounds. The same features have been identified over Lake Vostok and are an expected characteristic of deep-water subglacial lakes. In the cases of both lakes, the strength of the reflections from the ice–water interface varies near the shores, as a consequence of the reflector’s shape (Siebert et al., 2004).
2. In austral summer 2004–2005, the British Antarctic Survey flew a sounding line across Lake Ellsworth in the form of a bow, crossing the lake twice (Figure 1). Part of a 35,000 km grid pattern being collected over Pine Island Glacier also crossed the lake and identified other lake-like reflectors in the surrounding area. These lines were collected using 150 MHz ice-sounding radar (PASIN) (Vaughan et al., 2006). The new PASIN lines confirm the bright specular nature of the reflector and show a much shorter reflector than the 1977–1978 survey, of between 1.5 and 2.3 km in length. This suggests that the lake is long relative to its cross-profile, occupying a fjord-like basin on the flanks of the Ellsworth Subglacial Highlands.
3. In January 2006, a ground-based Chilean expedition traversed the Institute Ice Stream to Lake Ellsworth and acquired several RES transects over the lake.



Antarctic Subglacial Lake Ellsworth, Figure 1 (a) The location of Lake Ellsworth. The yellow box denotes bed information given in (c). Transect AB is provided in (b). (b) Raw 1977–1978 RES transect. The subglacial lake is located between 28 and 38 km. (c) Basal topography of the immediate area of Lake Ellsworth. (Adapted from Siegert et al. (2004).)

A 150 MHz RES system (CORDS) was used to collect nine lines totaling 15 km over the lake-like reflector (Rivera, personal communication 2006). These lines bound the lake to the north and west, though do not constrain its upstream margins to the south and east. Transitional zones are identified, showing a distinctly different radar response than that of the lake-like reflector or surrounding bedrock, possibly representing water-saturated sediments around the lake, thin water layers, or discontinuous water bodies.

Basal thermal conditions and ice flow modeling

The basal heat flux calculated in West Antarctica from temperature gradients in boreholes is around 70 mW m^{-2} (e.g., Hulbe and MacAyeal, 1999). Numerical thermodynamic evaluations suggest that the subglacial environment above Lake Ellsworth is warm, i.e., at the pressure melting point (Siegert et al., 2004). Due to increased ice thickness at the last glacial maximum (LGM), it is expected that the ice sheet was also warm based at the LGM. This indicates that Ellsworth may have existed during both the present interglacial and the LGM.

Ice flow modeling of the lake environment using internal layer architecture to invert for basal melting also suggests that the dominant process at the basal boundary condition is one of melting (Siegert et al., 2004). The model predicts that as ice flows over the lake, basal melting is expected at a rate comparable to the surface accumulation rate (which, near the ice divide, is $\sim 17 \text{ cm year}^{-1}$) (Siegert et al., 2004). This melt rate is significantly greater than that calculated for Lake Vostok, though is comparable to the situation in Lake Vostok in terms of its value as a proportion of the surface accumulation rate. As melting is the driving force behind water circulation (Mayer et al., 2003), the enhanced rates of melting predicted by the model may lead to circulation in Lake Ellsworth being stronger than Lake Vostok (and many other subglacial lakes). Upstream of Lake Ellsworth a small region of basal accretion is modeled at a rate of 20 cm year^{-1} . It is not yet known whether this freezing rate is real, or whether three-dimensional flow of ice (not accounted for in the model) complicates ice flow upstream of the lake and influences the internal layer structures. As the rate of water supplied to the lake is considerable, it is likely that Ellsworth is part of a wider subglacial hydrological network, feeding water into the basal environment of the Pine Island catchment.

Future research plans for Lake Ellsworth

A proposal to undertake a comprehensive geophysical survey of Lake Ellsworth, including ground-based RES, seismic surveying to calculate water depth in the lake and a variety of surface measurements, has been funded through the UK Natural Environment Research Council. The survey is planned in two seasons during the years of the International Polar Year (IPY) 2007–2009. Data collected during the IPY will supplement those acquired in 1978 and 2004–2006. As a consequence of these

geophysical results, Lake Ellsworth and its subglacial catchment will be characterized at a sub km resolution. It is a well-established hypothesis that Antarctic subglacial lakes house unique forms of life and hold detailed sedimentary records of past climate change. Testing this hypothesis requires in situ examination. Of the 145 subglacial lakes known in Antarctica, Lake Ellsworth stands out as a candidate for first exploration for the following reasons:

- The base of the West Antarctic Ice Sheet has been accessed, sampled, and measured. Accessing Ellsworth would, therefore, be less environmentally sensitive compared to accessing an East Antarctic subglacial lake.
- Lake Ellsworth is located close to the ice divide, so drilling from the ice surface into the lake will not be complicated by ice flow.
- Lake Ellsworth can be meaningfully characterized by geophysical methods.
- The sediments across the floor of Lake Ellsworth may contain a record of West Antarctic Ice Sheet history.
- The geological setting of the lake is better understood than any other Antarctic subglacial lake, as there is substantial outcrop of rock in the nearby Ellsworth Mountains.
- The ice sheet surface elevation over Lake Ellsworth is 2,000 m above sea level, more than a kilometer lower than the ice surface over East Antarctic subglacial lakes. Altitude-related problems encountered by scientists at the center of the East Antarctic Ice Sheet would not be an issue during the study of Lake Ellsworth.

A consortium of over 20 scientists from 7 countries and 14 institutions has been assembled to plan the exploration of Lake Ellsworth. Lake Ellsworth will be accessed using clean technology hot water drilling. Once lake access is achieved, a sterile probe will be lowered down the borehole and into the lake. The probe will contain a series of instruments to measure the lake water and sediments and will be tethered to the ice surface through which power, communication, and data will transmit. The probe will be dropped down the water column to the lake floor. The probe will then be pulled up and out of the lake, measuring its environment continually as this is done. Once at the ice surface, any samples collected will be taken from the probe for laboratory analysis. The duration of the science mission, from deployment of the probe to its retrieval, is likely to be between 24 and 36 h. Measurements to be taken by the probe include depth, pressure, conductivity, temperature, pH levels, biomolecules (using life marker chips), anions (using a chemical analyzer), nitrogen isotopes (using a tuned laserdiode), visualization of the environment (using cameras and light sources), dissolved gases (using chromatography), and morphology of the lake floor and sediment structures (using sonar). After the probe has been retrieved, a sediment corer may be dropped into the lake to recover material from the lake floor. Given that the comprehensive geophysical survey

of the lake will take place in two seasons during 2007–2009, a 2-year instrument and logistic development phase from 2008 (after the lake's bathymetry has been assessed) makes it possible that the exploration of Lake Ellsworth could take place in 2010–2012.

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Cross-references

[Antarctic Lakes](#)
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[Antarctic Subglacial Lakes](#)

ANTARCTIC SUBGLACIAL LAKE VOSTOK

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Introduction

Of the 145 subglacial lakes identified in Antarctica, the largest is Lake Vostok, the seventh largest lake on Earth (Studinger et al., 2004). Lake Vostok is situated in central East Antarctica at approximately 77°S and 106°E, between the Gamburtsev subglacial mountains and the

Aurora Subglacial Basin. A dense grid of radio-echo sounding (RES) records show that Lake Vostok is up to 260 km long and 80 km wide and the surface area is ~14,000 km² (Studinger et al., 2003). Local subglacial topography is very rugged to the west of the lake (ranging from –300 m to +2,400 m asl between the lake and 90°E), in contrast to smoother surfaces to the east (Studinger et al., 2003). A ~11 km wide and 30 km long embayment, separated from the main lake by a narrow bedrock ridge at the south-western shore, has also been identified (Studinger et al., 2003). The most recent geophysical surveys of the lake (consisting of laser altimeter, ice-penetrating radar, and gravity measurements) have shown that it consists of two sub-basins, separated by a ridge with very shallow water depths (Studinger et al., 2004). The southern basin is much deeper and approximately twice the spatial area of the smaller sub-basin to the north. Estimates of water depth from seismic investigations, RES-derived information about the bedrock slopes at the lake's margins, and aerogravity measurements, are several hundred meters and reach a maximum of 0.5–1 km near Vostok Station (Siegert and Ridley, 1998; Marsolov et al., 2001). The best estimate of the water volume based on aerogravity data is 5,400 ± 1,600 km³ (Studinger et al., 2004). The average ice thickness above the lake varies from ~4,300 m in the north to ~3,700 m in the south (Studinger et al., 2003), creating pressures in the lake in excess of 350 atm. The ice–water interface slopes downward from south to north with a gradient of ~0.002, which is 11 times that of the ice sheet surface, but in the opposite direction, implying the ice is in hydrostatic equilibrium with the underlying lake (Oswald and Robin, 1973).

Tectonic controls and lake history

The lake occupies a very large topographic depression, with a crescentic shape, similar to a rift valley. Lake Vostok may therefore occupy a rift valley formed by extensional tectonics, or may be a feature eroded by the ice sheet (Studinger et al., 2003) but most likely is a product of the two processes. There is presently no basis for estimating when the Vostok basin developed, but if it is linked in age with the Gamburtsev mountains nearby, this would be at least 30, and more likely >50, million years ago (Barrett, 1999). A liquid water lake formed in this depression when the ice became sufficiently thick to reach the pressure melting point (–3°C). The youngest possible age of lake water is the same as the ice at the base of the ice sheet, 420,000–1,000,000 years old. Some of the water could be as old as Lake Vostok itself if the lake is stratified (Siegert et al., 2003). It is thought that a subglacial lake could have existed in this location for as long as the ice sheet has been at a continental scale, which may be at least 15 million years (Summerfield et al., 1999). Sediments on the lake bed could be significantly older than the water if a subaerial lake existed prior to glaciation, provided that the advancing ice sheet did not scour them out of the basin.

Ice motion, subglacial melting, and freezing above Lake Vostok

Ice flow above Lake Vostok is NNW to SSE in the northern part of the lake, and W to E in the southern part (Tikku et al., 2004). Ice velocity measured using GPS and repeat-pass synthetic aperture radar interferometry (InSAR) from the ERS-1 satellite ranges from $3.0 \pm 0.8 \text{ m a}^{-1}$ to 4.2 m a^{-1} at Vostok Station (Bell et al., 2002; Kwok et al., 2000), such that ice would take approximately 15,000–20,000 years to cross the lake. The liquid water in Lake Vostok results from melting of the ice sheet in the north where the ice is sufficiently thick to reach the pressure melting point. Melting here is thought to be approximately balanced by lake refreezing to the underside of the ice sheet in the south, where the lake water is colder than the pressure melting point, so that the volume of water in the cavity does not change. Melt and freeze rates vary from a few millimeters to a few centimeters per year (Siegert et al., 2001; Bell et al., 2002).

Residence time and water circulation

Estimates of the residence time of water in the lake vary from ~40,000 to 300,000 years (after Bell et al., 2002 and Siegert et al., 2001). Circulation of water in the lake can only be predicted from theoretical models until the lake is accessed directly. Two possible scenarios have been modeled:

1. If the lake water is fresh, melt water formed in the northern region will be colder and denser than the resident lake water so will sink to the lake floor. Background geothermal heat will raise the temperature of this water above that of the overlying layers, decreasing the density and producing plumes of water that rise to the ice–water interface before cooling and sinking again.
2. If the lake water is saline, the fresh glacial meltwater will be buoyant compared with the resident lake water. The meltwater from the north would probably move southward and upward along the ice–water interface and eventually enter a region where it is below the melting point and refreeze onto the ice sheet.

Any circulation patterns are likely to be complicated by the Coriolis force and the complex geometry of the basins, which might introduce horizontal transfer and, to a lesser extent, vertical overturning (Siegert et al., 2003). However, there will always be an overall transfer of water from the north to the south (Siegert et al., 2001).

The chemical and biological composition of Lake Vostok

The composition of water in Lake Vostok has been inferred from ice retrieved from the bottom of a deep ice core above the southeastern corner of the lake. The so-called Vostok ice core has been drilled down to 3,650 m, stopping about 100 m above the lake's surface

in 2005. The top 3,538 m of the core is glacier ice and provides a detailed paleoclimate record spanning the past 420,000 years (Petit et al., 1999). The ice between 3,539 and 3,650 m has very different characteristics to the overlying glacial ice. The crystal size increases dramatically from a few cm to $<1 \text{ m}$, electrical conductivity decreases to the detection limit and numerous sediment particles are visible (Souchez et al., 2000). This ice has been interpreted as accretion ice, i.e., lake water frozen to the underside of the ice sheet. As this ice provides a sample of the lake water, it has been used to estimate the lake chemistry and biology.

Chemical composition

Soluble and insoluble impurities are added to the lake from the melting glacial ice and from the physical and chemical weathering of rock in the lake. The melting ice contains a very dilute mix of marine-derived aerosol, calcium-rich dust, and strong acids (e.g., nitric and sulfuric acid) (Siegert et al., 2003). Solutes are almost completely excluded from the ice crystals as freezing takes place, such that they are expected to build up in the lake over time until the inputs and outputs of solutes become balanced. However, the predicted salinity of the lake water from chemical analysis of the accretion ice is still very low and it would be classified as a relatively soft water lake (Wetzel, 2001). The idea of a very fresh water body agrees with the level of attenuation of radio waves in the water column that has been measured (Gorman and Siegert, 1999). The composition of the water is believed to be similar to runoff from other glacial environments, which is often characterized by rock–water interactions.

Sediments are introduced to Lake Vostok from the melting basal ice and the production of subglacial “rock flour.” Much of this material will remain suspended in the lake causing the water to be very turbid. Larger sediments will settle through the water column before accumulating on the lake bed. Although the melt rate is in the order of millimeters per year, sediments may have been building up gradually for millions of years, producing a layer tens to hundreds of meters thick. Sediments deposited across the floor of the basin before glaciation may not have been completely scoured by the advancing ice sheet, as a historical record from the mid-Cenozoic is present in the deepest sediments (Siegert et al., 2003).

Estimating the gas concentration in Lake Vostok is complicated by the existence of gas hydrates (gases trapped in cages of water molecules). Hydrates may partly or fully dissolve in the water, depending on the concentration of gases already present in the lake, but will remain stable after the dissolved gas concentration reaches a critical point, effectively buffering gas concentrations against short-term variations in source and sinks. Air will reach saturation in a minimum of 0.16–1.6 Ma (assuming contemporary melt and freeze rates) if there are no sinks within the lake and no significant transfers of water between other subglacial lakes. Therefore it is possible that the lake is already saturated with gas from the ice

sheet. The total dissolved gas in equilibrium with hydrates was estimated to be 2.5 l per kg of water (at 273 K and 1 atm) (McKay et al., 2003). Some gases may be utilized by chemical reactions (e.g., oxidation of reduced compounds) and biological processes. The consumption of gas by these processes may cause certain regions in the lake to become suboxic or anoxic, especially if the lake is stratified. For example, the oxidation of organic carbon in the sediments on the lake bed may deplete dissolved O₂ which cannot be replaced because of poor diffusion of gas in the sediments. The estimates of gas concentrations may need significant downward revision if Lake Vostok is found to be part of a connected hydrological system because gases will be able to leave the lake.

Biological composition

Microbial life is known to have developed biochemical, physiological, and morphological diversity to enable survival and growth in extreme temperatures, pressures, salinities, and pH values in environments containing liquid water (Rothschild and Mancinelli, 2001). It would therefore be surprising if some form of life was not present in Lake Vostok. Because the lake is permanently dark, organisms must either obtain their energy from organic matter in the lake (heterotrophic reactions) or make their own from chemical sources (chemoautotrophic reactions). The predicted dissolved organic carbon in the lake (<1,200 µg l⁻¹) is low, but adequate to support heterotrophic growth (Priscu et al., 1999). Total nitrogen concentrations in the accretion ice are sufficient to sustain ~10⁶ cells ml⁻¹ (Priscu et al., 1999). The life-supporting nutrients and gases, and hence any life, may be concentrated near the melting ice–water interface where they are introduced to the lake, or on the bed in the presence of nutrient-rich sediments.

Four independent laboratories have found very low counts and low diversity of bacteria in the accretion ice above Lake Vostok (Priscu et al., 1999; Karl et al., 1999; Christner et al., 2001; Abyzov et al., 2001; Bulat et al., 2004). Based on the cell concentrations in the ice and partitioning coefficients for the water to ice phase change, it is estimated that Lake Vostok contains 10⁵–10⁶ bacterial cells per ml (Christner et al., 2006). Metabolic and culturing experiments have demonstrated that a portion of the assemblage in the accretion ice is metabolically active when exposed to liquid water and nutrients (Karl et al., 1999; Christner et al., 2001).

Molecular identification of microbes within the accretion ice (by culturing and small subunit rRNA gene amplification) show close agreement with present-day surface microbiota, consisting of phylotypes within bacterial divisions Proteobacteria (alpha, beta, gamma, delta), Low G + C Gram positives, Actinobacteria, and the *Cytophaga-Flavobacterium-Bacteroides* line of descent (Priscu et al., 1999; Christner et al., 2001; Bulat et al., 2004; Christner et al. 2006). This may suggest that the bacteria in Lake Vostok do not represent an evolutionary

distinct community. The likelihood of a unique evolution in Lake Vostok depends on the timescale of isolation (how long microbes stay in the lake before being removed in the accretion ice) and whether the rate of evolution was sufficient to cope with the very high selective pressures in the lake. If Lake Vostok has survived since the onset of glaciation, the timescale of evolution could be as long as 15 Ma. This is not long enough for species-level divergence, but rapid genetic change may occur via recombination and mutator genes (Siebert et al., 2003). If microbes in the lake originated from basal sediments, they could be considerably older, such that they have been isolated long enough for evolutionary divergence. Unfortunately, the accretion ice only collects water from the surface of the lake and, therefore, may not capture ancient microbes that reside in deeper waters or on the bed.

Future exploration of Lake Vostok

In situ exploration of Lake Vostok is unlikely in the near future. Its colossal proportions and potentially distinct north and south basins make it very difficult to characterize in a meaningful way and make it unrepresentative of other subglacial lakes. Concerns over the potential contamination of the pristine environment will also have to be addressed. Further information about the planned exploration of subglacial lakes can be found in the entries for *Antarctic Subglacial Lakes* and *Subglacial Lake Ellsworth*.

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Cross-references

Antarctic Lakes
 Antarctic Subglacial Lake Ellsworth
 Antarctic Subglacial Lakes

ANTARCTIC SUBGLACIAL LAKES

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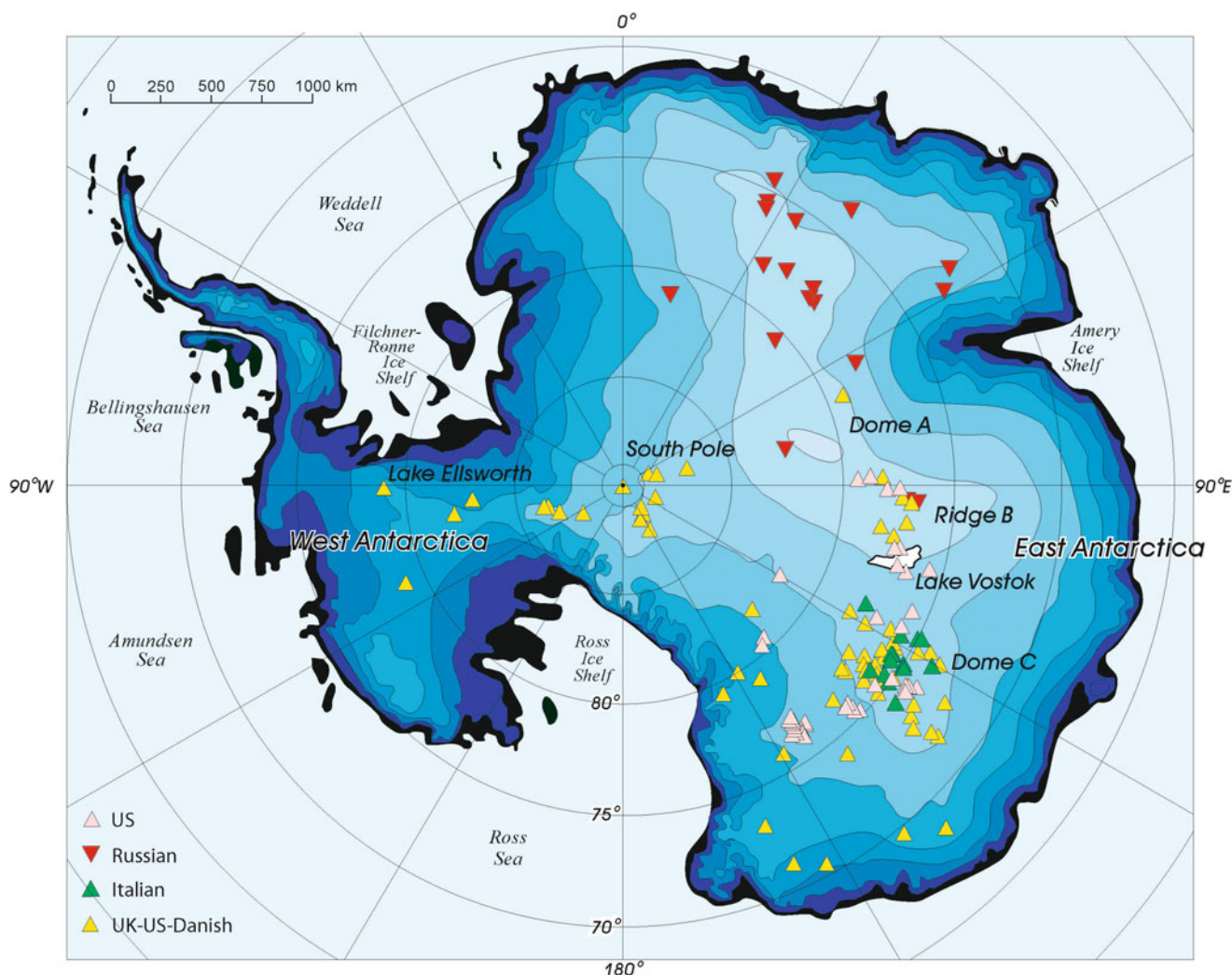
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Definition

Subglacial lakes are large pockets of water that lie beneath large ice sheets. Despite mean annual ice surface temperatures of below -50°C , background levels of geothermal heating ($\sim 50 \text{ mW m}^{-2}$) ensure that, where the ice is in excess of 3 km thick, basal temperatures can reach the pressure melting point. Subglacial water flows under the influence of gravity and ice overburden pressure. It can flow “uphill” if the magnitude of the ice surface slope is greater than 1/10th of the bedrock slope. Water collects, however, where basal slopes are larger, to form subglacial lakes.

Speculation about the existence of subsurface water in Antarctica took place in the 1950s and 1960s. The first reference to “lakes” in Antarctica was by a Russian pilot (R.V. Robinson) who identified features on the ice surface that resembled oval shorelines. The first evidence of subglacial lakes was derived from a technique called radio-echo sounding (RES), which utilizes VHF radio waves to measure the thickness of ice sheets in a manner analogous to seismic sounding. The technique was developed in the 1960s to comprehend the shape and volume of the Antarctic ice sheet. In the late 1960s and throughout the 1970s, RES was flown on long-range aircraft across approximately half of the Antarctic continent (and is still by far the largest of such surveys undertaken).

Subglacial lakes can be distinguished through three features of the reflected signal. First, the reflections are at least an order of magnitude stronger than from ice–rock contacts. Second, reflections are of constant strength across the lake, rather than the more common variable strength returns. Third, the surface of a subglacial lake is smooth and flat compared with the rough surrounding



Antarctic Subglacial Lakes, Figure 1 The location of 145 Antarctic subglacial lakes, shown as triangles with the exception of Lake Vostok, which is outlined. Colors refer to the surveys from which individual lakes were identified. (Adapted from Siegert et al. (2005).)

topography. Using these criteria enables the identification of subglacial lakes and, where more than one RES transect is available, their surface extents to be measured.

There have been three inventories of Antarctic subglacial lakes. The first listed the locations of 17 subglacial lakes (Oswald and Robin, 1973), the second provided details of 77 lakes (Siegert et al., 1996), and the third recorded 145 (Siegert et al., 2005) (Figure 1).

There are bound to be many more lakes, and so the final tally could be several hundreds. These inventories have revealed the size and distribution of Antarctic subglacial lakes including *Lake Vostok*, the largest and best known subglacial lake.

Recent research has discovered that, if subglacial lakes are fed with water, the pressuring effect results in sudden discharges, which may travel several 100 km, connecting several lakes together (Wingham et al., 2006). These

findings have changed opinions on whether subglacial lakes are isolated from each other, suggesting the lakes are interconnected in a hierarchical system of hydrological and therefore chemical and biological interchange.

Unless a lake is less than ~10 m deep, and its water is pure, the depth of water within a lake cannot be measured using RES because of the absorption of radio waves. Instead, seismic sounding must be used. Only three subglacial lakes have been measured using seismic sounding, however (*Lake Vostok*, in the south of the lake where the water depth is of the order of 0.5–1 km; *Lake Ellsworth*, where the water depth is ~150 m; and *South Pole Lake*, where the water depth is ~30 m). Hence, the volume of water held both within individual subglacial lakes, and in total beneath the Antarctic ice sheet, can only be estimated. If one assumes average water depths of between 50 and 250 m, the likely volume of water held in

subglacial lakes is around 6,000–22,000 km³ (equivalent to 15–70 mm of global sea level rise).

Subglacial lakes are not all the same. They can be characterized into at least three distinct groups: (1) those occupying entire subglacial hollows (including Lake Vostok); (2) those in relatively subdued topography, occupying only a small part of a larger subglacial trough; and (3) lakes that are “perched” across the stoss face of large subglacial obstacles.

Despite subglacial lakes being known about by glaciologists since the early 1970s, it took a seminal paper by Kapitsa et al. (1996), in which Lake Vostok was shown to be >500 m deep, to alert biologists to the possibilities of subglacial lakes as habitats for microbial life. If microbes exist in subglacial lakes, they must do so in permanent darkness and use chemicals, derived from ice melting into the lake and the rock and sediment beneath, to power biological processes. Subglacial lakes are therefore seen as analogous to extraterrestrial environments, such as the subsurface ocean of Europa. Furthermore, given that the East Antarctic Ice Sheet may have been in existence for up to 15 Ma, microbes in some lakes may have adapted in unusual ways to the extreme conditions encountered at the base of the ice sheet. Finding out whether microbial life exists in subglacial lakes is a driving goal of subglacial lake exploration, which has been in a planning phase for over a decade.

There have been six international meetings on Antarctic subglacial lakes (Cambridge 1994, St. Petersburg 1997, Washington DC 1998, Cambridge, 1999, Grenoble, 2006, Baltimore 2010). On each occasion, ways in which subglacial lakes can be explored have been discussed. It is particularly important to stress, given their pristine nature, that contamination of subglacial lakes must be avoided by exploratory programs. There are three ways in which a subglacial lake might be accessed: ice cores, thermo-probes, and hot water drills. While ice coring has been used to reach the bed of large ice masses on many occasions, it requires an antifreeze lubricant, which would be a major contaminant if it ever entered a lake system. Thermo-probes are devices that melt themselves downward into the ice, unwinding a tether to the surface as they do so. The advantage is that minimal contamination can be assured. The disadvantages are that much of the payload within the probe is taken up with the tether, restricting the science that can be done when in the lake, and the fact that the tether cannot be returned to the surface, which means that sample return is not possible. Tests on proto-type devices have been relatively unsuccessful, with problems of depth penetration and direction being caused by the sedimentary impurities within glacial ice. Hot water drilling, using a high-pressure hose to melt a hole in the ice, is a proven technique to access the beds of medium-sized ice sheets. It is gaining credibility as a means of exploring the base of large ice sheets. The advantage is that contamination can be restricted to melted ice (which is what lakes are made of). The disadvantage is that once melted, the borehole will refreeze,

limiting the period for an exploration experiment to little more than a single day. Several candidates for exploration have emerged in the last few years. One, named *Lake Ellsworth*, is worth noting as it is in West Antarctica. Here, the ice is much warmer and the location more accessible than for most lakes in East Antarctica, which makes exploration using hot water drilling feasible.

A second goal for subglacial lake exploration concerns the sediments that will accumulate on their floors. Glacial history of both the East and West Antarctic ice sheets is poorly understood, yet is critical to evaluating past global changes. For example, it is not known whether the East Antarctic ice sheet has remained in a stable form or not over the past 15 Ma. Moreover, despite acknowledging that the West Antarctic Ice Sheet is at risk of collapse, scientists currently have little idea as to when it last disappeared. Such information may be held within sedimentary material on the floors of subglacial lakes.

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Cross-references

[Antarctic Lakes](#)
[Antarctic Subglacial Lake Ellsworth](#)
[Antarctic Subglacial Lake Vostok](#)

AQUATIC PLANTS

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Introduction

Aquatic plants, frequently referred to as *macrophytes* or *hydrophytes* are an important functional component of many lakes and reservoirs (see, for example, Carpenter and Lodge, 1986). These terms are commonly applied to the vascular plants, mosses, and larger forms of algae (in particular filamentous algae and the stoneworts – Characeae) which are visible to the naked eye; smaller algae and phytoplankton are excluded. The vascular aquatic plants have not evolved in water but have descended from terrestrial plants. As such they show strong physiological similarities to their terrestrial

ancestors but exhibit some adaptation to submerged and waterlogged conditions (Sculthorpe, 1967). Most standing water bodies support some macrophytes and where they occur these plants are an important source of habitat and food for other organisms and have a key role in nutrient cycles and gaseous exchange through photosynthesis.

Growth forms

Plants growing in water exhibit a variety of growth forms related to the physical conditions in which they are growing and there is a clear link between life form and water depth. Aquatic plants are typically been divided into four categories – *emergent*, *submerged*, *floating leaved* and *free-floating* (Sculthorpe, 1967). However, these distinctions are arbitrary and some species exhibit different growth forms according to environmental conditions (environmental plasticity). Many species display different leaf forms depending on whether they are submerged or emergent. This *heterophylly* usually results in ovate, elliptic, or rounded emergent leaves and thin strap-like submerged leaves. The hydrology and morphology of the lake basin have a strong influence on both the presence and distribution of these different forms with emergents dominating in the shallower water areas and submerged species extending into deeper water (e.g., Pearsall, 1920).

Shallow water and periodically inundated areas on lake shores are characterized by *emergent* plants which grow rooted in substrate but have aerial photosynthetic parts (above the water surface). Emergent plants may grow in conditions that vary from waterlogged soils where water levels are up to 0.5 m below the surface to open water of 2 m depth. Although there are many dicotyledons with emergent growth forms, monocotyledons from the Poaceae (grasses), Cyperaceae (sedges), Juncaceae (rushes), and Typhaceae (reedmaces) tend to dominate in these conditions and can form extensive monospecific stands. These species commonly have large and extensive root systems and often spread through rhizomes. Emergent plants are a common feature of the *hydrosere* between open water and more terrestrial habitats and in lakes with shallow shorelines the emergent zone may be very extensive and part of a clear transition from terrestrial vegetation through to submerged flora. Such hydroseres are characteristic of semi-natural situations and are of high biodiversity value supporting a wide range of invertebrates and birds.

Submerged plants are those which grow with all photosynthetic parts beneath the water surface although in many species flowering parts may be held above the water surface to enable wind or insect pollination. Good examples are the exclusively aquatic plant families such as the Potamogetonaceae (pondweeds) and the Haloragaceae (water milfoils). Most submerged plants are rooted but compared to terrestrial and emergent species have reduced root systems. Other adaptations to submerged growth include limited woody tissue, thin cuticles, and large internal air spaces reflecting the additional support offered by

the surrounding water. Many submerged plants have finely dissected leaves which probably increase nutrient and light capture through their increased surface area (Wetzel, 1983).

Rooted plants with leaves that float on the surface of the water tend to have leaves with entire margins and thick waxy cuticles to minimize wave damage and water loss. Some species display heterophylly with both floating and submerged leaves of different forms. The ubiquitous water lilies (Nymphaeaceae) are the most well-known example of this life form. The *floating-leaved* growth form is generally restricted to water depths that allow leaves to reach the surface; in practice this is usually less than 2 m. However, some of the species in the group are able to grow in deeper water as submerged forms.

There is a further group of plants that are *free-floating* having no attachment to the substrate. These plants may be submerged such as the hornworts (Ceratophyllaceae) or more commonly surface floating such as the duckweeds (Lemnaceae). Free-floating plants generally spread through vegetative means, and as surface floating species are seldom light limited, they may spread rapidly. This propensity to spread and cover the water surface has the result that they may be invasive. Many of the invasive aquatic plant species which have caused economic or biodiversity problems have a free-floating growth form, for example, water hyacinth *Eichornia crassipes*.

Controlling factors

The distribution of macrophytes in lakes is determined by a range of factors but key determinants are light availability and wave exposure (see early work by Pearsall, 1920; Spence, 1967). Thus, macrophytes are generally confined to areas where light penetration is sufficient for photosynthesis and physical conditions allow relatively fine sediments to accumulate. Plant colonization depth is limited by light attenuation through the water column which is a function of water color and turbidity.

There is a relationship between light attenuation and depth of plant colonization. Macrophytes are restricted to the euphotic zone where net photosynthesis is possible; in practice for vascular plants this is the depth at which 1–5% of surface light remains (Wetzel, 1988). Where water transparency is very high it may be possible for Characeae or plants with an isoetid (low growing, rosette) growth form (e.g., Isoetaceae) to extend to more than 30 m. The ability of the Characeae to extend to greater depths may also be a function of pressure which may restrict vascular plants from the deeper areas (Spence, 1982). Some species particularly the stoneworts and some of the isoetid growth forms may form dense monospecific lawns at depth. Such growths are characteristic of particular lake types, for example, low-alkalinity oligotrophic lakes are characterized by isoetid species with different species commonly inhabiting different depths.

Clearly the amount of light energy reaching the leaf surface plays an important role in determining photosynthetic activity. Macrophytes compete with both phytoplankton and epiphytic algae (which use the plants as substrate) for light and nutrients (Phillips et al., 1978). This competition is a major factor in regulating the function of shallow lakes.

A major constraint to plant life underwater is the availability of carbon dioxide (CO_2). The diffusion of CO_2 in water is several orders of magnitude slower than in air and hence inorganic carbon availability may become a limiting factor for submerged plants. Some submerged plants have adapted to this through compensatory mechanisms using bicarbonate ions (HCO_3^-) as a source of carbon where free CO_2 is limited (Lucas, 1983) or aquatic acid metabolism (Cockburn, 1985). Plant nutrients such as phosphorus, nitrogen, and carbon may be important in determining the competitive relationship between macrophytes and algae but also on the actual species composition of macrophytes. There are well-established relationships between macrophyte communities and lake trophic status and documented species shifts with anthropogenic nutrient enrichment (Harper, 1992).

An important factor determining where plants occur within a lake basin is exposure to wave action. Exposed shores are unfavorable for plant growth as physical conditions prevent the buildup of fine nutrient rich sediments required for plant rooting and wave action physically damages plants. As a result in large basins plants tend to be concentrated in sheltered bays and areas of shoreline. Water level and the hydrological regime are also important in structuring emergent and submerged plant communities (Coops and Hosper, 2002). Groups of plants display different tolerances to water level and hence may be restricted to different areas of the shoreline and littoral zone. While plant communities may be adapted to seasonal fluctuations, fluctuations with much shorter return periods, often as a result of anthropogenic activities (e.g., hydropower schemes) are generally damaging, causing physiological stress to plants and leading to erosion (Hellsten and Riihimäki, 1996). For these reasons water supply reservoirs whether artificial or natural may have limited macrophyte communities.

Substrate is both an important source of nutrients and a means of anchoring for those plants which are rooted. There is an inter-relationship between sediment particle size and nutrient content. In general nutrient concentrations in sediments are orders of magnitude higher than in the water column and both emergent and submerged plants are known to obtain most of their nutrients from the substrate in spite of being able to source both phosphorus and nitrogen from the water column (Barko et al., 1991). Evidence suggests that sites of nitrogen and phosphorus absorption depend on a variety of factors including plant morphology (therefore species and phenotypes may differ in response); relative

concentrations in water and sediment; presence and type of organic matter; water column pH; and sediment density (see Denny, 1980).

The distribution of plants both within and between lake basins is also influenced by the modes of reproduction. Emergent species share many of the reproductive strategies of terrestrial plants and may be wind, water, or animal pollinated. Submerged species seem to be capable of sexual reproduction through seed but asexual reproduction through vegetative means prevails (Hutchinson, 1975). Aquatic species possess a range of different vegetative structures that enable them to reproduce modified stems such as stolons, runners, and rhizomes; modified buds such as turions; and specialized roots. As such long-range dispersal is highly dependent on water movements or animal vectors.

There is an affinity between certain macrophyte species or communities and particular lake types and as a result there have been a number of attempts to classify lakes according to their aquatic flora (Palmer et al., 1992). The visible nature of aquatic plant communities and these relationships between species composition and lake physical and chemical characteristics has led to aquatic plants featuring prominently in lake management and habitat conservation. However, this also reflects the important role that plants have in structuring communities of other organisms and controlling lake ecosystem function.

Functional role and importance

Where they occur plants may have a strong influence over in lake processes and overall ecosystem structure. Thus in shallow lakes where water depth allows plants to colonize large areas of the lake basin, overall lake function may be dominated by plants. Similarly the shallow littoral zone and sheltered bays of deeper lakes may be plant dominated. This influence is largely related to the effect of plants on nutrient dynamics and habitat structure.

Enrichment by phosphorus and nitrogen compounds leads to a range of undesirable impacts such as changes in macrophyte species composition at moderate levels of enrichment to the complete loss of submerged macrophytes and blooms of phytoplankton at high levels of enrichment (Harper, 1992). Macrophytes are in competition with phytoplankton for both light and nutrients. Under natural conditions where extensive macrophyte beds are present and external nutrient loads low, resultant concentrations of nutrients in the water column will also be low. Extensive beds of macrophytes act as a nutrient sink reducing phosphorus and nitrogen available for algae. Additionally, macrophytes stabilize sediments preventing resuspension of fine material and the associated nutrient flux to the water column and provide a refugia for zooplankton (e.g., large *Daphnia* spp.), invertebrates, and fish which graze on phytoplankton. Additionally the plants provide cover for large piscivorous fish (e.g., pike – *Esox*

lucius) which predate on smaller fish species that would otherwise suppress abundance and biomass of these phytoplankton grazers. Thus, macrophytes are important in mediating top-down controls on phytoplankton biomass.

These mechanisms are most pronounced in shallow lakes where plants can colonize extensive areas of the lake bed. It has been demonstrated that in these shallow lakes two alternative stable states can exist depending on the level of nutrient loading and the interaction of other factors (Scheffer et al., 1993; Scheffer, 1998). The macrophyte-dominated state as described is buffered by the effect of plants on other organisms and system. At high concentrations phytoplankton are able to shade out submerged plants leading to a loss of structure. This in turn reduces habitat for grazing zooplankton and predatory fish species. The number of small fish increases and in turn the size of zooplankton decreases, reducing grazing pressure. Thus, phytoplankton dominance reinforces the turbid water state. At intermediate nutrient concentrations either state is possible depending on other pressures. The introduction of bottom feeding fish, or the use of herbicides may reduce aquatic plant biomass acting as a “forward switch” toward a phytoplankton-dominated system. In management terms a “reverse switch” such as biomanipulation will be required to restore the lake to a plant-dominated state.

Although the interaction between macrophytes and phosphorus (and to a lesser extent nitrogen) has been the focus of much work and lake and reservoir management, macrophytes do influence other chemical and physical processes within lakes. For example, where there are abundant growths of submerged macrophytes high levels of photosynthetic activity can lead to short-term increases in pH and oxygen depletion. Equally submerged and emergent plant communities may be important in stabilizing accumulated fine sediments. Reduced exposure within stands may lead to sedimentation of particles and root structures may help improve the cohesiveness of substrate. The spread of littoral plant communities is a characteristic adjustment response where water levels have dropped and can have positive feedbacks by trapping more fine sediment and reducing water depth further.

As is evident from the alternative stable states model macrophyte stands provide important habitat complexity for other organisms. Emergent macrophytes of the littoral and shore zone are known to be important for fish recruitment providing a substrate for the eggs of some species and a refugia for fry. Birds also benefit from these stands of emergent vegetation and reedbeds are widely acknowledged to be important for many bird species. Macrophytes may also constitute an important food source as they may be a major source of primary productivity. A number of waterfowl species feed almost exclusively on submerged plants and many others may depend on fauna associated with these plants. Consequently deteriorations in water quality may affect associated bird communities as well as in lake flora and fauna.

Where they occur macrophytes are a vital component of standing water ecosystems exerting a strong influence upon ecological processes and trophic interactions. However, macrophytes are highly susceptible to the consequences of nutrient enrichment, a widespread pressure for standing waters. As a result macrophytes and the safeguard of these communities is often the focus of lake management especially where the concern is high-quality standing water ecosystems.

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Cross-references

[Eutrophication in Fresh Waters: An International Review](#)

ARAB REGION, LAKES AND RESERVOIRS

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Brief description of the Arab region

Physical geography

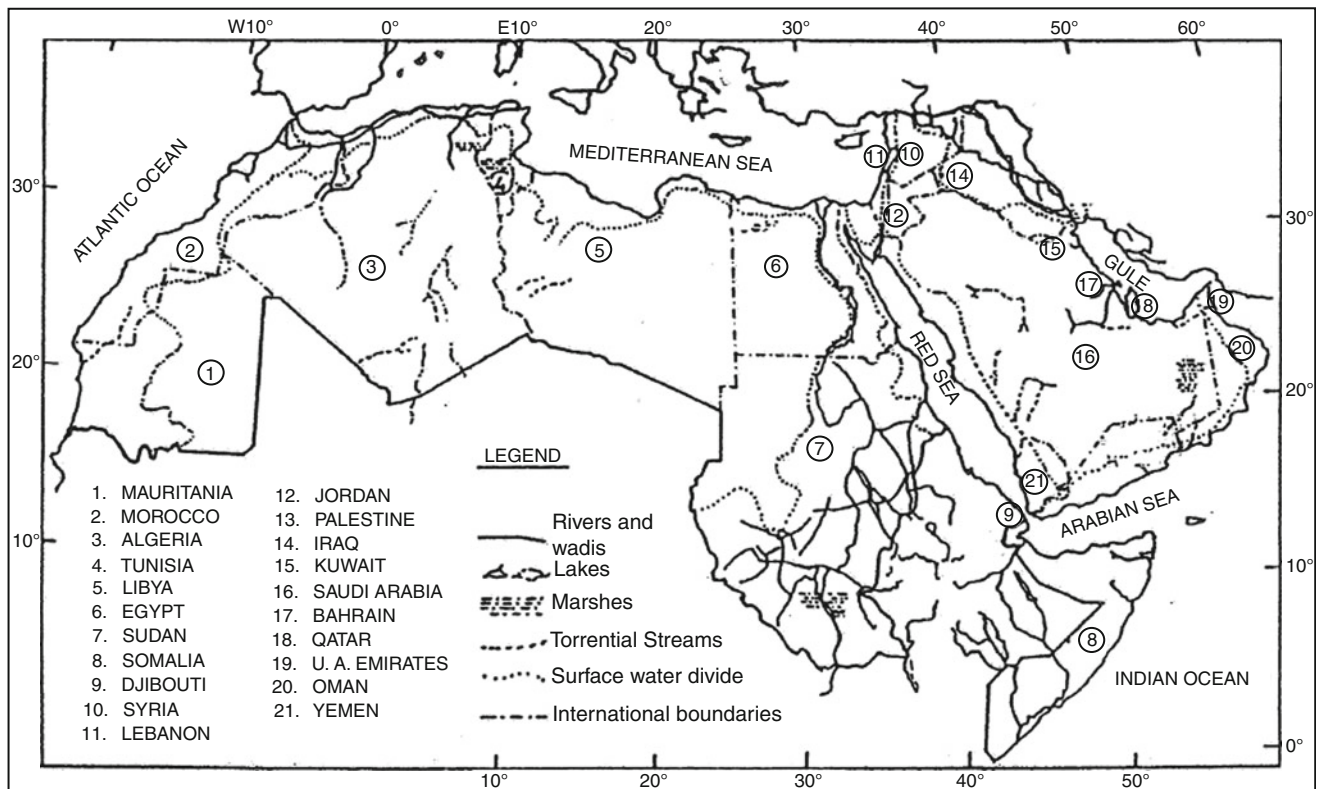
The Arab Region is a land surface situated between 1°35'S and 37°N latitudes and between 60°E and 17°W longitudes. It covers an area of about 14 km² extending from northwest Africa in the west to the Gulf in the east. The region is bounded by a seacoast 20,000 km long, which results in an overall average ratio of 1.5 m coastline per km² land surface. The region is occupied by 22 states distributed between three subregions. The western subregion includes Mauritania, Morocco, Algeria, Tunisia, and Libya; the central comprises Egypt, the Sudan, Djibouti, Somalia, and Comoro Islands; and the eastern subregion comprises Syria, Lebanon, Jordan, Palestine, Iraq, Kuwait, Bahrain, Qatar, Saudi Arabia, the United Arab Emirates, Oman, and Yemen (Figure 1).

Dry, warm deserts cover the greater part of the surface of the region. The Great Sahara extends from eastern Mauritania to Morocco and Algeria, and further to southern Tunisia. The name changes to Libyan Desert in Libya

and Western Desert in Egypt. The Eastern and Nubian Deserts cover the areas east of the Nile Valley in Egypt and the Sudan to the western shore of the Red Sea. A number of deserts occupy most of the area between the Red Sea in the west and the Persian Gulf in the east including the Arabian Peninsula.

The region encompasses diversity of mountain ranges: the Atlas in Morocco and Algeria; Al-Hoggar and Tibesti in Libya; Al-Uweinat in Libya, Egypt, and the Sudan; Darfur and Kurdufan in the Sudan; the Zagros in Iraq; Taurus in Syria; Al-Hijaz and Asir in the Arabian Peninsula. The Omani Mountains lie in a tectonically unstable zone. Two parallel ranges in Syria confine between them the Ghab Valley. Coastal mountain chains run parallel to the shores of the Mediterranean Sea, the Red Sea, Gulf of Aden (Yemeni and Hadramaut Mountains), and Gulf of Oman. The peaks of these mountains vary from 1,500 to 4,000 m a.m.s.l. (above mean sea level).

Next to high plateaus and mountain ranges, the Arabian deserts include low-lying areas in the form of coastal plains, oases, and swamps occupying flat depressions, large and deep natural depressions, and lakes. Most of the lakes are in the interior, without connection to the sea. Exceptions can be found in northern Egypt where some lakes open to the sea can be found. Salty lakes (Chotts) can be found in certain countries like Algeria and Tunisia.



Arab Region, Lakes and Reservoirs, Figure 1 Map of the Arab Region and the perennial rivers and major wadis traversing its surface.

Geology

The geological history of the region goes back to the Precambrian period (more than 500×10^6 year BP), in which time the "African Shield" was formed. Crystalline rock has been exposed in large surfaces in Mauritania, Algeria, Libya, and Egypt and the Sudan. It is also exposed along the coast of the Red Sea and the Arabian Peninsula, forming that branch of the African Shield known as the "Arabian Shield." The split of the Arabian Shield, which took place in the period $135\text{--}65 \times 10^6$ year BP, indicates to the geological destruction or tectonic activity that led to the formation of a huge depression filled by the Red Sea. The volcanic activity in the same subregion, though relatively recent, has strongly affected the Horan Plateau, Al-DrUz Mountain in Syria, northern Jordan, and Saudi Arabia. More recent tectonic movements led to the formation of mountains and are responsible of the subsidence of the Arabian Shield in the Rub al-Khali Desert, Persian Gulf, Euphrates, and Damascus region.

During the Paleozoic and Mesozoic Eras, ($310\text{--}135 \times 10^6$ year BP), thick layers of sand and Nubian were deposited on the basement rock in northern Sudan and the Western Desert in Egypt and Libya. Thick layers of limestone were deposited later in the Mesozoic Era, 120×10^6 year BP in the Arabian Peninsula thereby increasing the material overlying the basement rock. Alternating series of lacustrine calcareous rock and sand were deposited during the Tertiary and Quaternary Eras in many areas in the region and formed Al-Hamada in Algeria and Morocco. The same deposits augmented by layers of limestone are present in Egypt, Syria, Iraq, and the southern part of the Arabian Peninsula. The Atlas region belongs to the Mediterranean region and is characterized by formations where clays, calcareous rocks, and dolomites of the Jurassic Period are dominant.

The unstable shelf of the Arabian Platform in the eastern subregion appears in the form of basins and swells in Syria, Jordan, and the Gulf States. The transition zone of the unstable to the stable shelf extends from Sinai to the Gulf of Aqaba and follows the Wadi Araba, Jordan. In Syria, it trends eastward and south eastward while in Saudi Arabia it trends southward and parallels the Persian Gulf. The Nubian-Arabian Shield occupies southern Sinai and the surroundings of the Gulf of Aqaba and Red Sea as far as the northern border of Yemen. Clastic sediments of continental rocks of the Precambrian basement complex characterize these areas.

Climate

The region is a transitional area between the equatorial and mid-latitude climates, with June–August as the warmest period of the year and December–February as the coolest period. Maximum day temperatures above 40°C occur for long periods in certain parts of Iraq, Saudi Arabia, Western Sahara, and the Egyptian-Sudanese borderlands. Summer temperature ranges between 30°C and 35°C in Syria, Iraq, Jordan, and Palestine, and gets higher on the coasts of the

Red Sea and Gulf of Aden. Contrarily, the temperature on the coasts of Libya, Tunisia, Algeria, Morocco, and on Al-Hoggar and Tibesti Mountains in Libya and the Yemeni Mountains is below 30°C . The summer night temperature in all said locations is at least 10°C lower than the respective maximum temperature. The minimum winter temperature is below 5°C in the northern Sahara and Libyan Desert, and below 0°C in the higher parts of the Atlas region. It rises at the Red Sea and the Arabian Sea coasts, and in the Rub al-Khali Desert to $10\text{--}15^\circ\text{C}$. In the southern tip of the Red Sea and the Gulf of Aden, it exceeds 20°C . The maximum day temperature in winter season is 20°C along the Mediterranean coast, 10°C or below in the Atlas region, below $10\text{--}12^\circ\text{C}$ in Syria, above 15°C in Mesopotamia, and $20\text{--}25^\circ\text{C}$ at the Red and Arabian Sea coasts (Martyn, 1992).

The eastern subregion is generally dry nonetheless well differentiated. The December relative humidity in Mesopotamia, the Gulf coast, the southern half of the Red Sea coast, and the Gulf of Aden is above 70%. In the same month, it is below 40% in the Rub al-Khali Desert and 30% in the Yemeni mountainous region. The relative humidity in June–August, driest season of the year, is above 65–70% along the Mediterranean and Red Sea coasts decreasing to 30% inland and 20% in Central Mesopotamia and Saudi Arabia. The monsoon causes the humidity to rise to 50–60% in the south of the Peninsula and around the Gulf of Oman and Persian Gulf. Over North Africa, it is low throughout the year. In the early morning hours of January, it falls from 80% to 90% along the coast to 40% inland. The July humidity can be between 5% and 20% in the Sahara causing the air to be dry to very dry.

Winter cloudiness in the Arabian Peninsula, except in mountainous areas, is 20–30% and rises to 45–60% in northern Syria and Iraq. Summer cloudiness in the Mediterranean region is 10–20%. The annual number of cloudless days is 300 at Aswan, Egypt, and over 100 in the Western Sahara including the Mediterranean coast. The Central and Eastern Sahara receive over $3,600 \text{ h year}^{-1}$ of sunshine increasing to more than 4,000 h in the Libyan, Nubian, and Arabian Deserts. Southward, the hours decrease as the rainy season becomes longer (2,900–3,000 h in southern Mauritania). Clouds blowing off the Atlantic also reduce the sunshine to 2,600–3,000 h on the coastal plain of Morocco, the High Atlas, and the coast of the West Sahara. Due to cloudiness mainly, the annual effective sunshine varies from 3,100 h in northern Iraq and on Lebanon mountainous to 3,300 h over Babel-Mandab Straits and in the interior of the Arabian Peninsula. The sunshine is least in January, ranging from 150 h in Lebanon, northwest Syria, and northern Iraq to 250 in southern Iraq and 300 h in southwest Saudi Arabia. The sunshine duration in July exceeds 400 h in the Syrian Desert and north Saudi Arabia, and 250 h in Yemen.

Those parts of the region in West Asia between 20° and 30°N receive annually above 200 kcal cm^{-2} extraterrestrial radiation. The January radiation increases from

4 kcal cm⁻² in Lebanon and western Syria to above 8 kcal cm⁻² along the line running from the Gulf of Aqaba to central Iraq, and further to 12 kcal cm⁻² in Bab el-Mandab Straits. In North Africa, the January radiation increases from 8 to 10 kcal cm⁻² in the north to 16 kcal cm⁻² in the south. The July radiation in the Syrian Desert can exceed 20 kcal cm⁻² while in the southern part of the Peninsula it falls to less than 18 kcal cm⁻². Martyn (1992) added that the solar radiation in the Sahara of North Africa is 200 kcal cm⁻² year⁻¹ increasing to 220 kcal cm⁻² year⁻¹ in the reach of the Nile Valley between Aswan, Egypt, and Abu Hamad, the Sudan, corresponding to 85–90% of the possible maximum extra-terrestrial radiation. The solar radiation is reversed in July bringing the energy to over 22 kcal cm⁻² in the Western Sahara along with the Libyan and Egyptian coasts. Westward the radiation energy reduces to 18–20 kcal cm⁻².

Aridity is a principal feature of the region. Precipitation, mainly in the form of rainfall, ranges from more than 1,000 mm year⁻¹ in certain parts of the Sudan, Lebanon, and Morocco to zero in desert areas. The available literature (e.g., Shahin, 1989) estimates the average annual rainfall in the region as 1.9×10^{12} m³ year⁻¹ or 140 mm year⁻¹.

Rivers and wadis

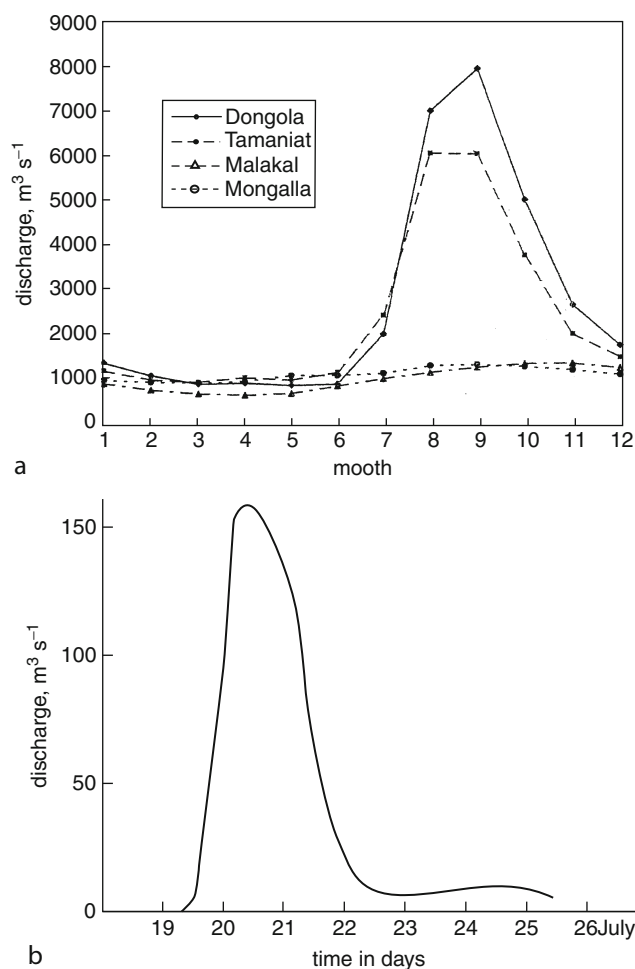
The mightiest river in the region is the Nile River system. It has been suggested that the Nile was made up of several subsystems each is related to a different geological time. The tectonic movements, which took place in the central subregion, have helped to establish hydraulic connection between the elements composing these subsystems. The Euphrates and Tigris Rivers, alike the River Nile, are international rivers. The Tigris supplies some of its water to Iraq while the Euphrates supplies some of its flow to Syria and Iraq. The River Senegal supplies Mauritania with its allocated share of water. This is not the case with the Shebelle and Juba Rivers, which flow naturally from Ethiopia to Somalia bringing whatever water left unused by the upstream countries. Wadi Zeroud (Tunisia), Cheliff (Algeria), and Sebou (Morocco) are national rivers. The principal feature of river flow in the region is its seasonality. The ratio of maximum to minimum flow is in the order of 10:1 (Figure 2a).

The surface of the region is intersected by a tremendous number of intermittently flowing watercourses (wadis) of different sizes, amounts of flow, and sediments. As the minimum flow is practically zero (Figure 2b), it is obvious that the seasonality of wadi flow can be considered as infinite. As the distribution pattern of the supply is different from that of the demand, water storage in reservoirs seems to be indispensable in many cases.

Lakes and reservoirs

Hydrology and water quality aspects

Before embarking on any presentations of lakes and reservoirs in the Arab Region, it might be worthwhile to start



Arab Region, Lakes and Reservoirs, Figure 2 (a) Long-term average hydrographs of the Nile River at four key stations. (b) Hydrograph of the Black Gorgol Wadi, Mauritania.

by a brief review of a host of items of general nature to lakes and reservoirs anywhere in the world.

Definition and classification of lakes and reservoirs

A lake is a relatively isolated stretch of water filling a depression mainly of natural origin. A lake system consists of a body of water and a basin. Lake basins, according to Smith (1998), are formed by certain activities such as: tectonic, volcanic, glacial, fluvial including shoreline processes, and wind action.

A reservoir is a natural facility where stream flow is stored in times of excess to be released in times of shortage. The contents of a reservoir, water and silt, begin to accumulate following dam construction. Flow regulation after a reservoir is put into operation serves one or more purpose(s) such as flood protection, irrigation, hydro-power development, navigation, domestic, and recreation. Reservoirs can be classified as small, medium, and large. Depending upon its operation, reservoir storage can be seasonal, annual, and over-a-year.

Effect on climate and environment

Lakes and reservoirs tend to modify the climates of the surrounding areas. Their effects vary with the areal extent and depth of water, configuration, characteristics of prevailing wind, and the general climatic environment within which the lake interacts. Large, deep lakes develop more substantial modifications than small, shallow lakes; the effects in areas of pronounced seasonal change are more significant than those in tropical areas. Eichenlaub (1998) attributed these effects to alterations of the boundary layer caused by thermal lag of lake surface temperatures and differences in moisture budget of lakes compared to temperature and moisture of the surrounding areas; alteration of winds by lakes due to changes in surface roughness; and to interactions of the three factors.

Thermal stratification is an important physical feature of a lake. The sun heats the water surface thus decreasing its density and resulting in the formation of a layer of less dense water (epilimnion) overlying a denser, cooler layer of water (hypolimnion). A transition layer (thermocline) separates these two layers. Shallow tropical lakes stratify and destratify more than twice a year while deep tropical lakes do not completely mix.

Major reservoirs have their environmental influences on the surrounding areas such as micro-climate change, leakage of water, induced earthquakes, and landslides. Water temperature changes, turbidity, eutrophication, and sedimentation do happen within the reservoir itself. Riverbed change, bank erosion, salt accumulation in river delta soils, deterioration of soil fertility, seawater intrusion, coastal erosion, and effects on wildlife and fishes are among the influences that might take place downstream the reservoir. Dam construction and reservoir storage also have their societal influences, for example, landscape preservation, forced displacement of population, protection of archeological relics, and development of water-borne and water-related diseases (Hori, 1991).

Eutrophication

Eutrophication can be defined as the enrichment of waters with plant nutrients, primarily phosphorus, and nitrogen leading to an accelerated plant growth (e.g., algae) above and beneath the water surface. When decaying, this plant material leads to depletion of the oxygen reserves of water bodies causing problems such as deterioration of water quality for drinking purposes, fish mortality, liberation of corrosive gases, and other undesirable substances which is a recreational and environmental impairment, and impairment of the holding capacity (OECD, 1982).

Depending on the amount of phosphorus, average water depth and mean water residence time, a reservoir or a lake can have eutrophic and oligotrophic zones separated by a mesotrophic zone. The ensuing eutrophication problems of natural lakes, estuaries, lagoons, and closed seas in North Africa have been described as identified while those of reservoirs, rivers, and irrigation systems are serious problems (Meybeck et al., 1989).

Morphometry

The important dimensions of the water body of a lake are the maximum and mean of each of the length, width, and depth. The effective length, relative depth, lake area, lake volume, volume development, and the relationship describing the change of surface area with depth are equally important. Hutchinson (1957) and later Kuusisto (1985) gave expressions combining these dimensions to establish the necessary parameters of the water body.

Mass balance of a lake

The balance of any system such as water, heat, salts, and sediments is an expression of equilibrium and is identical in all cases. The input part of the water balance of a lake consists of the direct precipitation and the inflow of surface and groundwater while the output consists of lake evaporation and the outflow of surface and groundwater. The sum of input items over a certain period of time added to the initial volume of water in storage reduced by the sum of outflow items over the same period gives the final volume of water in storage at the end of the chosen period. The difference between the initial and final volumes is equal to the change in storage.

Lake chemistry and mineralization

The chemical composition of lake water depends on the rock composition of the lake and its drainage basin, connection to the seawater, quality of runoff to the lake, and on the climatic zone. According to their mineralization (quantity of salts in solution), lakes can be grouped into freshwater (up to 1.0 g L^{-1}), brackish ($1.0\text{--}24.7 \text{ g L}^{-1}$), saline ($24.7\text{--}50 \text{ g L}^{-1}$), and hyper-saline (over 50 g L^{-1}).

Sedimentation

Saline and freshwater lakes have different deposits. The former may be predominantly evaporites interrupted by clastic sediments brought into the lake during sudden flooding. The sediments in freshwater lakes vary considerably in response to the nature of origin of the lake basin, character of the rock, and soil around the basin, characteristics of the drainage area, extent of shallow water near the shorelines, and the organisms dwelling in the lake. Recent deposits in most freshwater lakes are highly organic. Varves, which occur in lakes receiving or have received at some time in their history water from melting ice sheets, might be of interest to detect.

Reservoir sediments are mostly products of erosion processes taking place in the upper reaches of the catchment area. As the land slope decreases, the eroded material begins to settle in streambeds, flood plains, or in lakes and reservoirs. The sediments in this case are mostly of mineral origin. Part of the deposited sediments leaves the reservoir through dredging, by flushing, or is transported by the release to the downstream. The volume of sediments still left in a reservoir divided by the volume of sediments that entered it, both in a certain period of time, is called trap efficiency. This efficiency plays a major role in determining the life age of a reservoir.

Lakes in the Arab region

The region as described earlier includes a number of natural lakes and depressions. Some of these lakes are situated along the seashore and the rest are in the interior. Sixteen out of the twenty-two countries sharing the Arab Region do not have any natural lake of substance. These countries are: Morocco, Libya, the Sudan, Djibouti, Somalia, Comoros, Lebanon, Palestine, Jordan, Kuwait, Bahrain, Qatar, Saudi Arabia, United Arab Emirates, Oman, and Yemen. Lakes, chotts (saline, shallow lakes), and depressions that can be found in the remaining countries are given distributed on respective countries in Table 1.

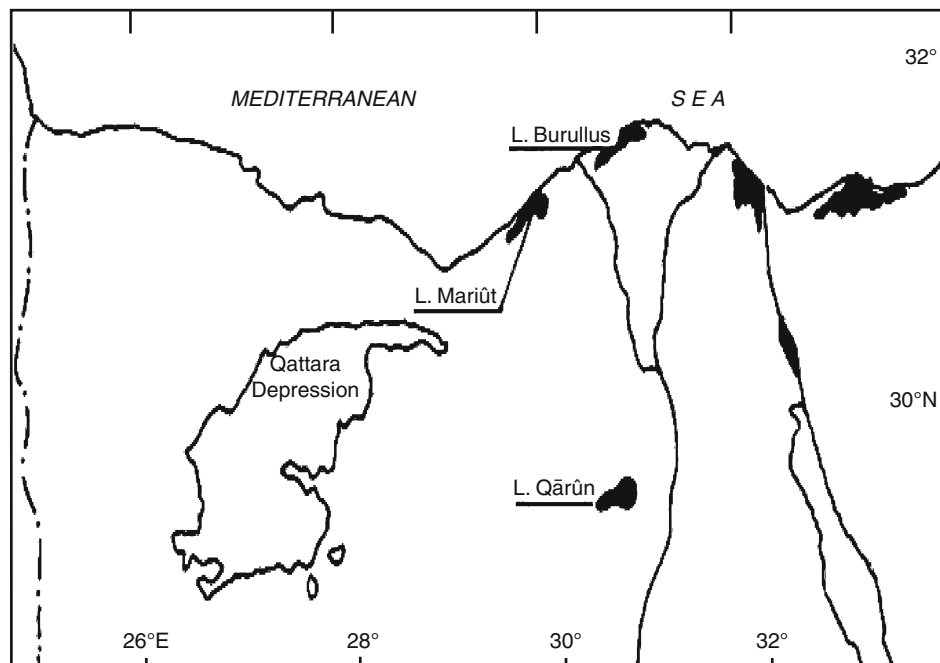
The major characteristics, especially the water balance and quality of water, of some of the above-listed lakes and depressions are briefly reviewed in the next subsections.

Arab Region, Lakes and Reservoirs, Table 1 Major lakes in the Arab region distributed on countries

Mauritania	Lake Rkiz
Algeria	Cholt el-Hodna, Ch. ech-Chergui, and Ch. Melhrir
Tunis	Lake Meleh, L. Oubeira, L. Tonga, L. Benzert, L. Ichkeul, Chott Gueltar, Ch. Jerid, Ch. Fejaj, Ch. elGharsa, and Ch. el-Franji
Egypt	Lake Al-Zaranik, L. Bardawil, Great and little Bitter Lakes, L. Timsah, L. Manzalah, L. Burullus, L. Mariut, L. Edku, L. Qiirln, and Qattara Depression.
Syria	Lake Horns, L. Ateibe, L. el-Hijane, L. el-Ghuba, L. Khabrat Seiqal, and L. Khabrat Abu al-Husan.
Iraq	Lake Habbanyah, Bahr al-Milh, and Tharthar Depression.

Lake Burullus, Egypt. Al-Burullus Lake is a shallow, brackish lake situated along the Mediterranean coast and occupies a central position between the two branches of the Nile River in the Delta area (Figure 3). It is connected to the sea by a narrow outlet, 44 m in width. The lake is about 65 km long and 6–16 km wide. The present surface area of the lake is about 410 km² of which 370 km² is open water with a depth ranging between 0.42 and 2.07 m. The eastern part of the lake is the shallowest, with an average depth of 0.8 m. The lake volume at zero level is 328×10^6 m³. The lake bed overlies deposits of clay and sandy facies up to 1,000 m thick in the western part. Their absence in the eastern part may be related to erosion of an old branch of the Nile River. The catchment area of the lake is located between 30°22'00"–31°36'16"N latitudes and 30°29'00"–31°21'19"E longitudes. The elevation varies from about 20 m at the most southern edge to zero at the sea in the north with an average slope 0.00015.

The southern shore of the lake receives the agricultural drainage water of 74.3% of the Nile Delta region. The volume of water thus supplied is about 3.9×10^9 m³ year⁻¹. The discharge varies from 100 m³ s⁻¹ in February to 160 m³ s⁻¹ in July. Besides, the lake receives a mean annual rainfall (1912–1992) of 187 mm corresponding to 77.4×10^6 m³. Model studies have shown that the annual groundwater inflow to the lake can be estimated as 32.5×10^6 m³. As such, the total inflow to the lake is about 4×10^9 m³ year⁻¹. The lake evaporation has been estimated as 647×10^6 m³ and the seepage flow to the sea has been estimated from the difference in head between the lake and the sea, the hydraulic resistance of the top layer and the transmissivity of the deposits



Arab Region, Lakes and Reservoirs, Figure 3 Location map of some of the lakes and natural depressions in Egypt.

underlying the lake. The balance of inflow–outflow components using the flood routing technique yields an outflow to the sea of $3.2 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. It is worthwhile to report that the tide estimated as the difference between the mean high water (0.33 m) and the mean low water (0.18 m) is small and its effect can be neglected.

Recent analysis of the drainage water has shown that the concentration of BOD ranges between 34 and 64 mg L^{-1} and of COD between 56 and 91 mg L^{-1} . The concentrations of heavy metals are rather low; 0.473–0.914 for iron, 0.002–0.476 for zinc and 0.013–0.184 for copper, all in mg L^{-1} . Biological activity, especially at certain sections of the lake is high. This has been attributed to the intensive application of nitrate and phosphorus fertilizers to the agricultural lands served by the drainage system. The Drainage Research Institute of Egypt (2004) observed that certain species of fishes and migrating birds are disappearing, there are marked changes in the chemical and bacteriological properties of lake water and indications to health impairment among some of the fishermen.

Lake Mariût (Mareotis), Egypt. This is one of the smallest natural lakes in Egypt. It is isolated from the Mediterranean Sea, extending some 10 km along the coastal strip of the sea west of Alexandria and 30 km to the south (Figure 3). The area of the lake was estimated in 1950 as 168 km^2 at elevation 3.0 m b.m.s.l., 714 km^2 at zero m.s.l. and 840 km^2 at elevation 1.0 m.a.m.s.l (Shafei, 1952). The figures given by the Water Researches Center, Egypt, lately show that the gradual drying up of certain portions of the lake and filling in of other parts have led to the reduction of the lake area at mean sea level from 252 km^2 in 1989 to 172 km^2 in 1920 to 137 km^2 in 1965 to 63 km^2 in 2000.

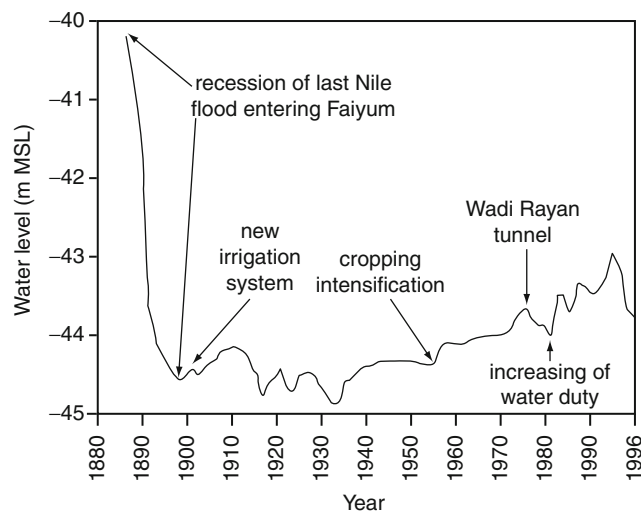
The annual rainfall on the lake was estimated as 0.145 m and the annual evaporation as 0.87 m (Shafei, 1952). The drainage flow to the lake has been recently estimated as $0.435 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. Most of this volume is sanitary and industrial drainage water, some of which is drained into the lake without being treated due to the inadequacy of the existing plants. The organic material in the lake water is high (in the order of 50%), except in the northwestern and southwestern sections where it ranges from 4.7% to 6.3%. It has been suggested to begin with clearing the lake from the heavy deposits accumulated in it, removing the surface and submerged plants crowding the lake, draining water into the lake after treating it and stopping filling in any new parts of the lake.

Lake Qārûn, Egypt. The Fayoum Depression is in the Western Desert of Egypt. North of the depression lies Lake Qarful, which is the lowest part of the depression. The lake is situated between $29^\circ 24'$ and $29^\circ 32' \text{N}$ latitudes, and $30^\circ 24'$ and $30^\circ 49' \text{E}$ longitudes. It is an inland, isolated lake having an elongated shape and a surface area of 240 km^2 . The average length, width, and depth of the lake are 40 km, 5.7 km, and 6 m, respectively. The normal water level is about 44 m b.m.s.l. corresponding to

a capacity of $960 \times 10^6 \text{ m}^3$. Up to 1973, the lake served as out-fall escape to all drainage water of the agricultural land of the Fayoum Province. Since then, 30% of this water has been diverted to Wadi el-Rayyan Depression, which lies in the Fayoum Depression. The inflowing drainage water is mostly exhausted by evaporation from the lake. The annual rainfall and evaporation, averaged over the period 1960–1972, were 0.009 and 1.725 m, respectively. The average depth of drainage water for the same period was 2.036 m. Considering a net seepage flow of $66 \times 10^6 \text{ m}^3 \text{ year}^{-1}$, one can draw the water balance of the lake for the period 1960–1972, which indicates an annual rise of 4.3 cm or $10.34 \times 10^6 \text{ m}^3$. This figure agrees with the recorded average rise of 3.62 cm year^{-1} for the said period. The results obtained by Mankarious (1979) continued until 1978 to cover a period of 5 years after the inflow of the drainage water to the lake has been reduced. Ali et al. (2000) continued the study further up to 1996. The change in water level in the period 1860–1996 is presented in Figure 4.

Drainage canals carry annually 0.5 Tg of salt to lake Qārûn. As no salt leaves the lake, the water quality is rapidly deteriorating. The annual mean salinity for the years 1906, 1931, 1970, 1989, and 1996 was 14.0, 34.3, 39.6, 45.0, and 50.0 dS m^{-1} , respectively. One should not forget that the salinity of the Nile water is 0.4 dS m^{-1} and of the Mediterranean Sea is 25 dS m^{-1} . It is expected that the quality of the lake water by the year 2020 will be hazardous due to its high level of salinity causing disastrous impairments to agriculture, fishing, and tourism.

While water temperature at any particular depth varies over the season, it is only in summer that any appreciable stratification could be observed (0–4 m vs 5–8 m). By not including the summer thermal stratification, one can conclude that the lake can be considered as isothermal with well-mixed temperature (Ali et al., 2000).



Arab Region, Lakes and Reservoirs, Figure 4 Changes in water level of Lake Qārûn over the past century (By permission of Ali et al., 2000).

Qattara Depression, Egypt. The Qattara Depression, an under-sea-level depression, ranks next to the depression of the Caspian Sea in its largeness. Its deflated basin is the outcome of wind activity. The depression is situated roughly halfway between the Nile Valley and the Egyptian-Libyan border (Figure 3), with a total length from ENE to WSW of almost 300 km. The depression is bounded to the north and west by steep escarpments with a difference of elevation of 200 m. The shortest distance between the depression and the Mediterranean Sea near the town of Alamein is 80 km. The surface area of the depression at sea level is about 20,000 km² decreasing to 13,500 km² at 50 m b.m.s.l. The volume of contents at m.s.l. is about $1,200 \times 10^9$ m³. The eastern part of the depression is more shallow and narrow than the western and central parts. The deepest point of the depression is about 133 m b.m.s.l.

The area occupied by the depression is dry. The average freshwater evaporation as estimated by Flohn and Wittenburg (1980) using four methods, Dalton, heat budget, Penman, and Mcilroy, is 1.75 m. Several studies have been conducted with the aim of connecting the depression to the sea through a system of lined canals and tunnels so as turn the depression to a saltwater lake. To reach the design storage level of 50 m b.m.s.l., which can be reached within 16–20 years after the project starts, the inflow discharge should vary from $1,200 \text{ m}^3 \text{ s}^{-1}$ in the first half of the filling period to about $750 \text{ m}^3 \text{ s}^{-1}$ in the second half. The latter inflow rate will be balanced by the outflow, which is evaporation from the newly formed lake. The end result of those studies is to examine the feasibility of utilizing the head difference (50 m) to generate hydropower for the industrial development in Egypt.

Hydrochemical studies have proven that the Mediterranean water has low nutrient content. In 1976–1977, the nitrate–nitrogen concentrations were 0–23 mgL⁻¹ at the surface and 0–6 mgL⁻¹ at 100 m depth. The phosphate concentrations too were 0.3–3 mgL⁻¹ at the surface and 0.3–3 mgL⁻¹ at 100 m depth. Zero concentration indicates that the nutrient supply at times is locked up in organic matter. Only Silica exhibited a clear seasonal variation with a distinct winter minimum. The oxygen concentrations varied from down to half saturation in deep waters to full saturation in surface waters (UNGI Report No. 62, 1985).

In conclusion, the studies, which lasted from 1916 up to the 1980s and later, did not lead to any conclusive results except that the environmental assessment has not revealed any serious objections to the implementation of the project. The effects of the project on the groundwater levels, flows, and chemical and other characteristics remain, however, one of the major obstacles that need to be solved before any definite decision can be taken.

Al-Tharthar Depression (Reservoir), Iraq. The Tharthar depression is a natural depression that has become since 1956 a fresh water reservoir. Since then, it

has been rehabilitated in 1972 and 1976. The depression, which is slightly deeper than 3 m b.m.s.l., lies between the Euphrates and Tigris River. Its surface area increases from 400 km² at sea level to 955 km² at 25 m a.m.s.l. and further to 1,826 km² at 50 m a.m.s.l. to reach 2,460 km² at 62 m a.m.s.l. The inflow to the reservoir comes from Wadi al-Tharthar and the excess of the Tigris flow above a certain limit. The water in storage is diverted to the Euphrates in times of deficit. The reservoir is designed for irrigation and flood control purposes. The monthly flow of the Wadi Tharthar and the surrounding watersheds is: 20, 35, 30, and 15, all in 10^6 m^3 , for December, January, February, and March, respectively. The respective mean monthly rainfall is 30, 40, 40, and 30 mm. Evaporation varies from 80 mm in January to 400 mm in July. The normal and maximum retention levels and the dead storage level are 62, 65, and 42 m, respectively. The design capacities are $77.6 \times 10^9 \text{ m}^3$ and $85.4 \times 10^9 \text{ m}^3$ for the normal and full reservoir levels, $38.5 \times 10^9 \text{ m}^3$ for live storage, and $7.8 \times 10^9 \text{ m}^3$ for surcharge storage.

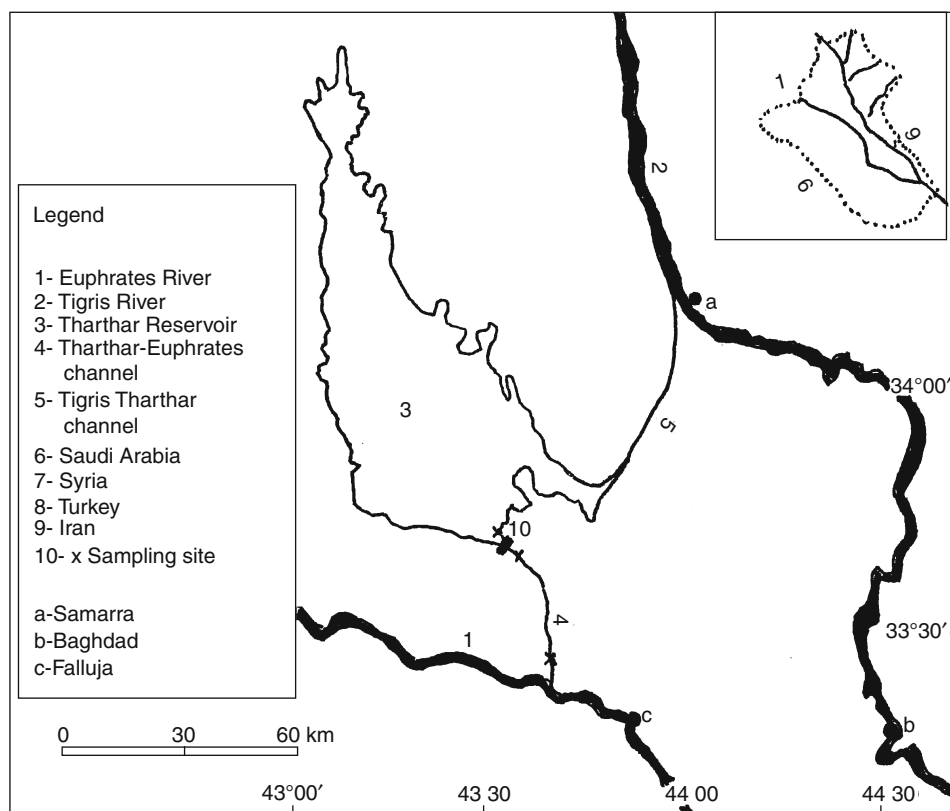
The monthly average solute concentrations of the reservoir water ranged from 1,990 to 2,240 ppm for the period 1983–1984. In order to detect the variations in water quality along the Tharthar-Euphrates channel (Figure 5), water samples were collected and analyzed for the major cations K, Na, Mg, and Ca, and anions Cl, SO₄, and HCO₃. The average solute concentration for the channel water during the same period ranged from 1,980 to 2,300 ppm. The results have also shown that there is no significant relationship between the solute concentration and the water discharge. The rate of suspended material transported through the channel is quite limited and it too has no relationship with water discharge (Al-Dabbas and Al-Jiburi, 1986).

Reservoirs in the Arab region

The Arab countries, at least some of them, are crowded with dams, consequently a large number of storage reservoirs. Most of these dams are small, low dams. The subsections given below present in brief some of the main features characterizing some of these reservoirs.

Storage reservoirs in Morocco. Moroccan wadi basins are equipped with a fairly large number of dams for irrigation and hydropower development. Besides, there are several dams under construction and/or planned for construction in the various wadi basins. A data summary of the existing reservoirs in Oum er-Rebia and Sebou Basins is given in Table 2.

Idriss-I reservoir is the largest storage work in the Sebou Basin. Its filling was completed in 1973. The long-term annual rainfall at a location near the reservoir is about 620 mm, most of which falls in the months from September to June. The Colorado Pan evaporation at El-Kansara reservoir on Wadi Beth ranges from 47 mm in January–February to 183 mm in July–August, with a total of $1,283 \text{ mm year}^{-1}$. The mean annual discharge of Wadi



Arab Region, Lakes and Reservoirs, Figure 5 Location map of Al-Tharthar Depression, Iraq.

Arab Region, Lakes and Reservoirs, Table 2 Data of some of the existing reservoirs in Morocco

Name of dam	Wadi/location	Year of construction	Gross capacity (10^6 m^3)	Regulated flow (10^6 m^3)
<i>Oum er-Rebia and Tensift Basins</i>				
Sidi Saïd Maachu	Oum er-Rebia	1929	N.A. ^a	N.A.
Kasbet Tadleh		1931	100	280
L'iemfut		1944	N.A.	N.A.
Ad'Dawra		1950	N.A.	N.A.
Bine el-Oudiane	Wadi Abid	1953	1,500	880
AyetWarda		1954	N.A.	N.A.
Moulaya Youssuf	Wadi Tessaout	1970	200	260
Al-Masierah	Wadi Oum er-Rebia	1979	2,724	1,360
Lalla Takarcost	N'ffis	N.A.	78	65
Ayet Shwarit	Wadi al-Akhdar	1988	270	350
Dashr el-Wadi	Wadi Oum er-Rebia	1990	740	485
<i>Sebou Basin</i>				
Kansara	Wadi Beht	1935	272	210
Idriss-I	Wadi Inaouene	1973	1,270	990

Inaouene at Azib es-Soltane (1934–1988) station was $62.8 \text{ m}^3 \text{ S}^{-1}$. The normal full storage level is 217 m a.m. s.l. corresponding to about $1.1 \times 10^9 \text{ m}^3$ useful storage. The difference between this amount and the gross capacity is allocated for dead storage. Further development of the Sebou Basin, particularly to protect the Rharb Plain from the floods originating from the Sebou and its tributaries,

has prompted a fresh review of all existing and planned reservoirs in the basin.

Storage reservoirs in Syria. According to Water Authorities in Syria, the sum of the capacities of existing, under construction, and planned for construction reservoirs is $12.07 \times 10^9 \text{ m}^3$, of which the Euphrates (Assad or

Ath-Thawra) Reservoir alone has a total storage capacity of $11.6 \times 10^9 \text{ m}^3$, that is, 96.1% of the grand total storage capacity. The dam construction was completed in 1974. It is 40 m high and has a surface area at full storage level of 625 km^2 . As the three countries (Turkey, Syria, and Iraq) sharing the Euphrates River have not yet resolved their conflicts, we shall present here the reservoir water balance using the original design data.

The catchment area of the reservoir is $64,100 \text{ km}^2$, the reservoir precipitation and evaporation are 0.28 and 2.0 m year^{-1} , respectively, and the runoff coefficient is 10%. The inflow to the reservoir

$30.01 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ is the sum of the inflow from the springs, 1.6×10^9 ; groundwater inflow, 0.4×10^9 ; the flow of the Euphrates received from the upper reaches of the river basin, 26.8×10^9 ; and the surface runoff, 1.21×10^9 , all in $\text{m}^3 \text{ year}^{-1}$. As the mean annual flow estimated from the old flow measurements at Husseiba on the Syrian-Iraqi border was $23.61 \times 10^9 \text{ m}^3$, the difference between the inflow and the outflow shows that Syria benefits from the reservoir by $6.4 \times 10^9 \text{ m}^3 \text{ year}^{-1}$.

Storage reservoirs in Jordan. Jordan has a relatively large number of storage works under construction or planned for construction in addition to the already existing dams/reservoirs. In view of its limited water resources, however, storage reservoirs in Jordan are of small effective capacity. Table 3 gives some of the particulars of the existing dams/reservoirs with total capacity larger than $5 \times 10^6 \text{ m}^3$ (Malkawi and Abdulla, 1997; Al-Kharabsheh and Ta'any, 2005). The sum of the total capacities of the reservoirs listed in Table 3 counts to 82% of the total capacity of all existing reservoirs and to 64% of the existing and under construction reservoirs.

The survey published in 1997 lists Al-Wahda dam under the group of Dams yet to be constructed. The idea goes back to 1956 to store the waters of the Yarmouk River at Maqarin near Irbid where the mean river flow is $273 \times 10^6 \text{ m}^3 \text{ year}^{-1}$. According to some agreement between Jordan and Syria, the construction of some preliminary works was carried out and completed in 1989. The strong opposition of Israel to the implementation of the project has brought it to a halt (Murakami and Musiaki, 1994).

Storage reservoirs in Egypt and the Sudan. As the Nile River system is the major water supplier to Egypt and the

Sudan, and the management of this source is done jointly between these two countries, particulars of the storage reservoirs are listed together in Table 4. The High Aswan Dam (HAD) is a long-term storage work aiming at full control of the river flow. The reservoir at storage level 170 m a.m. s.l. has a surface area of $4,308 \text{ km}^2$. As evaporation alone is in the order of 2.5 m year^{-1} the total loss of water at the said level can be estimated as $11 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ reducing the long-term mean natural flow of the Nile at Aswan from $84 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ to $74 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. As the sum of the annual volumes of river water used by Egypt and the Sudan in the pre-dam condition was $52.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$, the gain due to storage is $21.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. This amount has been divided such that $7 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ is allocated to Egypt and $14.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ to the Sudan, bringing the respective shares of Egypt and the Sudan to $55.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ and $18.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. These shares are proportional to the populations of the two countries by the time the reservoir was put into operation.

The reservoir formed by the Aswan High Dam is a multipurpose storage work aiming at providing water for newly cultivated lands, developing hydropower, protecting land and properties against floods, and improving inland navigation. On the other hand, the reservoir failed to modify the harsh climate and environment of the surroundings. Instead it resulted in inundation of certain areas in Nubia and many of its inhabitants had been forced to migrate. Additionally, the sediment flow downstream of the dam has stopped and substituted by artificial fertilizers, which require a lot of hydropower to manufacture. Vast tracts of the land downstream of the reservoir suffer from poor drainage conditions, and the sediment-free flow condition is causing the retreat of the seashore line and disappearance of certain species of sea fish.

Recharge reservoirs in the Arabian Peninsula. Some States of the Arabian Peninsula have been for quite some time embarking on dam construction programs to utilize as much as possible the surface water runoff and to enhance a better management of their limited water resources. The number of dams constructed from the mid 1980s to the mid 1990s has reached 265 as specified in Table 5. The advantages of the artificial recharge reservoirs are twofold: water conservancy and mitigation of the impact of rainfall variability on agriculture. Due to major differences in topography and relief of the ground, one finds that the majority of dams in Saudi Arabia and

Arab Region, Lakes and Reservoirs, Table 3 Data of some of the storage reservoirs in Jordan

Dam/reservoir	Year of construction	Location	Dam height (m)	Effective capacity (10^6 m^3)	Total capacity (10^6 m^3)
Kafrein	1976	Balqa	46.0	2.5	8.5
King Talal	1986	Zarqa	108.0	75.0	80.0
Wadi el-Arab	1984	Irbid	82.5	16.9	20.0
Karamah	2001	Balqa	N.A.	7.8	55.0
Hasa Tanour	2002	Taifa	69.0	7.8	16.8
Wala	2003	M'adaba	45.0	9.3	9.3

Arab Region, Lakes and Reservoirs, Table 4 Data of the storage reservoirs in Egypt and the Sudan

Name of dam/ reservoir	River/ distributary	Period of construction	Maximum storage level (m.a.m.s.l. ^a)	Design storage capacity (10 ⁶ m ³)	Remarks
<i>Egypt</i>					
Old Aswan ^b	Main Nile	1898–1933	106.0, 113.0, and 121.1	1.06, 2.3, and 5.2	First/second/third heightening, respectively
High Aswan	Main Nile	1960–1972	182.0	162	90 × 10 ⁹ m ³ live storage
<i>The Sudan</i>					
Sennar	Blue Nile	1925	420.7	0.80	Low sedimentation rate
Jabal Awlia	White Nile	1934–1937	377.2	3.5	<2 × 10 ⁹ m ³ presently
K. el-Girba	Atabra	1960–1964	N.A.	1.3	40 × 10 ⁶ m ³ year ⁻¹ sediment
Roseires	Blue Nile	1961–1966	480	3.0	First phase of storage
Merowe	Main Nile	Under	N.A.	N.A.	Hydropower generation

^aMeter above mean sea level^bNo longer in operation after the construction of the High Aswan Dam**Arab Region, Lakes and Reservoirs, Table 5** Data of the recharge dams built in the period 1985–1995 in the Arabian Peninsula

Country	Number of constructed dams	Range of storage capacity, 10 ⁶ m ³	Number of dams under construction or planned to be constructed
Saudi Arabia	190	0.01–32.5	9
United Arab Emirates	35	0.25–18.5	5
Yemen	17	0.50–369	12
Oman	14	0.01–12.5	32
Total	256	0.01–369	58

Yemen are in mountainous regions because of the availability of surface runoff generated by the frequently occurring rain events. Differently, most of the recharge dams in Oman and the United Arab Emirates are built on wadi channels in flat areas, especially those close to the seacoast.

Most of the recharge reservoirs in Saudi Arabia are designed to hold the flowing surface runoff in the particular wadi at the site where recharge of the underlying aquifer is desired. The recharge is supplied from a surface source of relatively large area. This method is often criticized on the grounds that the evaporation loss is high, and secondly the rate of infiltration into the aquifer decreases accumulation of silt and other deposits in the reservoir. The latter can be eliminated or reduced through periodic removal of these deposits. Some pieces of literature (e.g., Al-Hassoun and Al-Turbak, 1995) discuss the efficiency and management of such reservoirs.

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Cross-references

[Lakes as Archives of Earth History](#)
[North Delta Lakes, Egypt](#)
[Water Balance of Lakes](#)

ARAL SEA

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Synonyms

Aralskoye more; Lake Aral

Definition

The Aral Sea is a major salty lake in Central Asia, situated approximately between 44° and 47°N, and 58° and 61°E, at the border of Uzbekistan and Kazakhstan, two newly independent states of the former Soviet Union.

Introduction

Until 1960, the Aral Sea was the world's fourth largest lake in area, yielding only to the Caspian Sea, Lake Superior, and Lake Victoria. At the time, the Aral Sea volume was 1,060 km³, the surface area was about 66,000 km² and the maximum depth was 64 m. The absolute lake level varied only slightly around 53.4 m above the ocean level.

The terminal lake was fed by two tributaries, Amudarya River and Syrdarya River, providing together for 56 km³ of freshwater inflow on the long-term average. At the

time, the Aral Sea was a brackish water body. Its salinity spanned around 10 g/kg and never exceeded 12 g/kg. Generally, the water mass of the lake was spatially uniform: Except the estuarine areas of the rivers, the difference between the surface and bottom salinities was merely a few tenths of g/kg. The seasonal cycling of salinity was largely negligible (e.g., Kosarev, 1975). At the same time, temperature demonstrated rather energetic variability, both spatial and temporal, at different scales. The seasonal range of the SST was over 25°C, and horizontal SST gradients often exceeded 6–8°C per 100 km. The vertical stratification of temperature was also typically strong: In the bottom part of the western trench (depths over 60 m), temperature remained nearly constant at 2–4°C throughout the year, while the near-surface water masses in summer were as warm as 23–25°C, forming a steep thermocline at 20–30 m depths. Hence, the density fields were mainly governed by temperature rather than salinity. In consequence of the mild vertical stratification of the pre-desiccation Aral Sea, the entire water body of the lake was fully ventilated down to the bottom in all seasons. Moreover, most of the Sea was oversaturated with oxygen. The overall average content of oxygen was 6.3 ml/l, or 101% of the saturation value, but oversaturation as high as 180% has been observed near the northeastern shore (Blinov, 1956). The conditions of the brackish, fully ventilate lake favored biodiversity – for example, the Aral Sea accounted for 5–10% of fishery catches of the USSR.

In 1960, the lake level started to drop continuously. It is generally believed that the shallowing was mainly anthropogenic, and followed an increase of water diversions from the tributary rivers for agriculture. Some data and models, however, suggest that the desiccation was triggered, at least partly, by natural climate variability (e.g., Bortnik and Chistyayeva, 1990). Paleoclimatic reconstructions indicate that the Aral Sea has undergone several similar shrinking episodes in the distant past, always followed by subsequent recoveries (e.g., Boomer et al., 2009).

Recent changes in the physical state of the lake

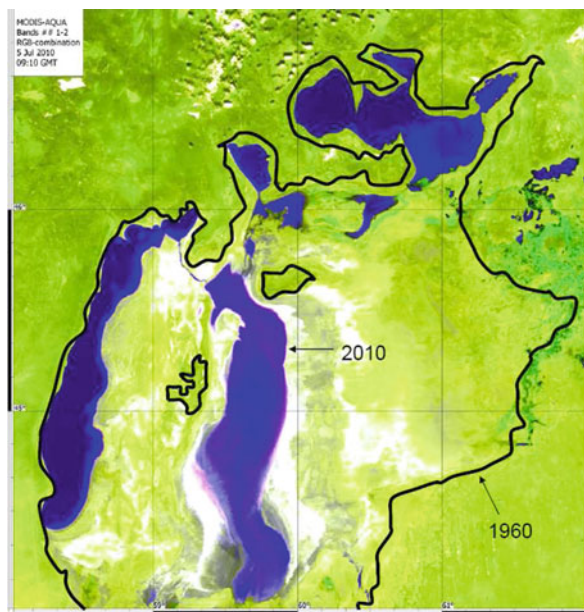
The Aral Sea's desiccation is known as one of the world's worst ecological disasters of the kind. By the date of this writing (October 2010), the total level drop was about 26.6 m. The Aral Sea has split into several separate water bodies, of which the most notable are the so-called Small Sea in the north and the Large Sea in the south (Figure 1). The latter consists of now almost separate western and eastern basins, connected through the narrow channel. Today, the western basin remains relatively deep (up to 38 m), while the eastern basin is extremely shallow (less than 2 m). Because of differential heating in summer, the shallow eastern basin is subject to very intense evaporation. This is why, in the last years, the salinity in the eastern basin was, generally, much higher than that in the western one. Overall, with its today's volume of only about 90 km³, including 50 km³ in the Large Sea and 40 km³ in the Small Sea, the lake has lost over 90% of its water (Figure 2).

The shrinking of the Aral Sea has been accompanied by a continuous salinity buildup. The most recent salinity figures available on the date of this writing (data obtained in August 2009) are 136 g/kg for the western Large Sea, and over 210 g/kg for the eastern Large Sea, constituting notable increase by respective factors of 13 and 21 since 1960. As to the Small Sea, in 2005–2006, the Kazakhstan authorities built a permanent dam isolating the Small Sea from the rest of the lake, and effectively trapping the

discharges of Syrdarya Rivers in the Small Sea. In consequence, the salinity in this part of the lake decreased and continues decreasing.

A key feature characteristic for the “new” state of the Aral Sea, in contrast with its regime prior to the desiccation onset and that at the initial stages of shrinking, is the vertical stratification. The first of the recent survey conducted in 2002 immediately revealed the salinity difference as high as 12 g/kg between the upper mixed layer (82 g/kg) and the bottom layer (94 g/kg). According to the available previous hydrographic data, namely, the data of 1990 (Bortnik and Chistyeva, 1990), the Aral Sea was still well mixed at that time. We, therefore, can only conclude that the strong vertical stratification first appeared sometime between 1990 and 2002, and the exact dating is unknown. However, there are reasons to believe that this may have happened in 1996–1997. The stratification continued to build up since then. It has been shown that the principal source of stratification in the western Large Aral is the water from the saltier, denser eastern basin, penetrating into the western lobe through the connecting strait and eventually accumulating in the deep layers (Zavialov, 2005, Zavialov, 2009). Typical vertical profiles of temperature and salinity in the deepest part of the Aral Sea (observed in August 2009) are shown in Figure 3. The near-bottom salinity maximum seen in this figure is attributed to the admixture of water from the shallow eastern basin.

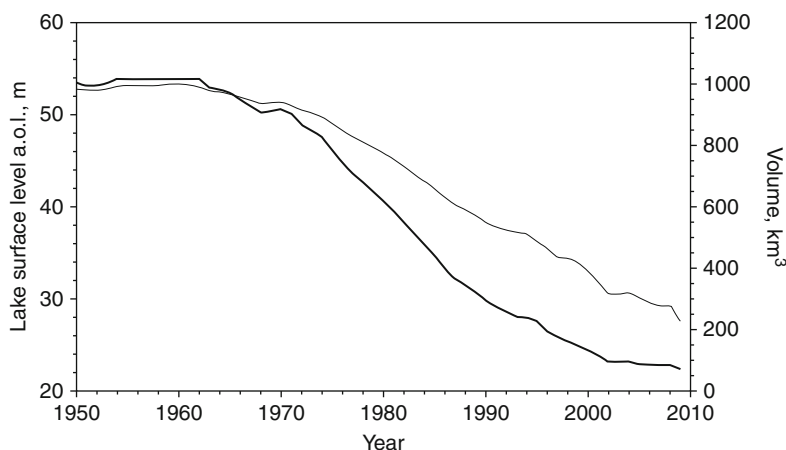
Recent velocity measurements in the lake demonstrated that the basin-scale circulation of the Large Aral forms an anticyclonic gyre in the surface layer, and a cyclonic gyre in the bottom layer. Intense internal wave activity in the pycnocline, which may be an important mechanism of the lake mixing, was documented (Zavialov et al., 2009).



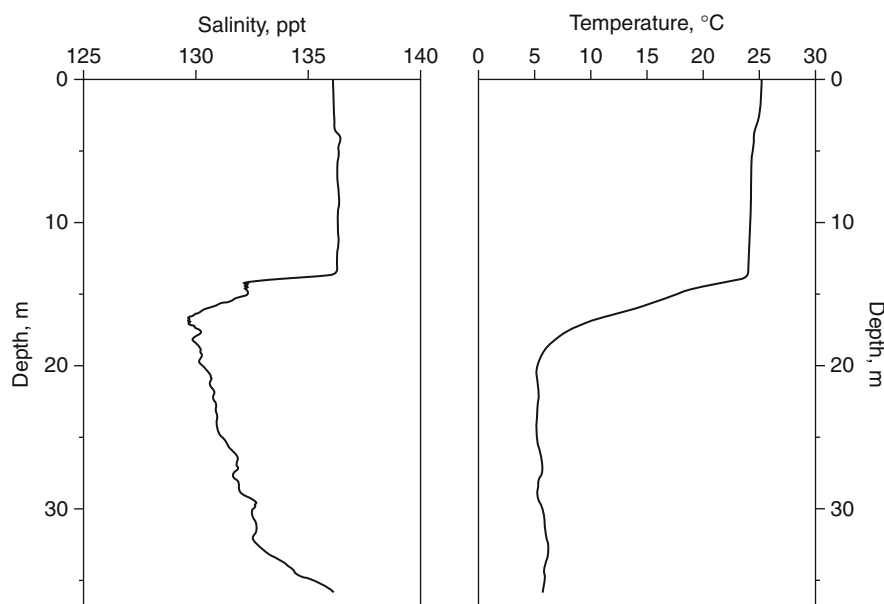
Aral Sea, Figure 1 Original shore line of the Aral Sea (as of 1960) superimposed on a recent satellite image of the lake (MODIS-Aqua scanner, July 5, 2010). The northernmost water body is the Small Sea, the western and the eastern basins of the Large Sea are seen in the southwestern part of the figure, interconnected through the narrow strait.

Other important issues

The desiccation resulted in significant alterations in not only physical state of the lake, but also its chemical regime. As mentioned above, prior to the desiccation onset



Aral Sea, Figure 2 The Aral Sea level drop (*fine curve*) and volume shrinking (*bold curve*) for 1950–2009.



Aral Sea, Figure 3 Vertical profiles of temperature (*right*) and salinity (*left*), typical for the advanced stage of the Aral Sea desiccation. August 2009, central part of the western basin.

in 1960, the entire Aral Sea was always saturated with oxygen. This situation continued through the initial decades of the desiccation in 1961–1991, but significantly changed sometime between 1991 and 2002. By the late 1990s, enhanced density stratification had arisen, largely impeding vertical mixing and ventilation. As a consequence, the bottom portion of the column turned anoxic and contained hydrogen sulfide. The H_2S contamination was first observed in 2002 (Zavialov, 2005) and persisted since then, at concentrations ranging from 5 mg/l to 80 mg/l, although intermittent ventilation episodes associated with winter convection were also documented (Zavialov and Ni, 2009). The depth of the upper limit of the sulfide-containing layer varied from 15 to 35 m.

Even before the desiccation onset, the Aral Sea water already had rather peculiar salt composition, which was quite different from that of the ocean water, as well as many other saline lakes. The contemporary desiccation has led to significant additional alterations of the chemical composition. During the desiccation, the salt composition of the Aral Sea has been subject to continuous changes because of chemical precipitation accompanying the salinity buildup (Bortnik and Chistyeva, 1990). As the salinity increased initially, the first compounds to precipitate were the calcium and magnesium carbonates. The subsequent salinization led to the massive precipitation of gypsum. According to (Bortnik and Chistyeva, 1990), this major process started when the salinity exceeded 28 g/kg, i.e., in the late 1980s. Processes which took place at higher salinities include the precipitation of mirabilite and halite (Rubanov et al., 1987). The total masses of minerals sedimented from the onset of the

desiccation through 2008 are estimated as follows: gypsum, 2.3 billion tons; mirabilite, 1.9 billion tons; halite, 0.4 billion tons; carbonates of calcium and magnesium, 0.2 billion tons.

Obviously, the large-scale precipitation of the salts must have led to significant changes in the salt composition of the remaining water mass of the lake, so that today's figures differ considerably from those known for the pre-desiccation period. The relative concentrations of the principal ions before and after the desiccation are shown in Table 1.

It is evident that the relative contents of the ions changed significantly during the desiccation. The most pronounced changes occurred with Ca^{2+} whose relative concentration decreased ninefold, from 4.6% to only 0.5%. Of course, this must have been expected, because the precipitation of both calcium carbonate and gypsum consumes calcium. The sulfate ion, also consumed in gypsum precipitation, decreased in relative content as well, from 31% to 23%. In contrast, the relative content of Cl^- grew from 34% to 43%. In consequence, the mass ratio $\text{SO}_4^{2-}/\text{Cl}^-$ decreased from 0.90 to 0.52, i.e., by 42%. Also strongly reduced by about a factor of 2.5 is the content of the bicarbonate ion HCO_3^- which was consumed by the formation and precipitation of calcium and magnesium carbonates. The relative content of sodium increased from 22% to 25%.

The abrupt changes of the physical and chemical conditions of the Aral Sea led to severe consequences for the biological systems of the lake. The present situation is less alarming in the Small Sea, where even fisheries are now recovering. However, in the principal part of lake, the Large Sea, the last specie of fish (flounder)

Aral Sea, Table 1 Relative contents of the principal ions in the Aral Sea water in 1952 and 2008

Ion	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Na ⁺	Mg ²⁺	K ⁺	Ca ²⁺
Content (%) 1952	34.5	31.1	1.5	21.9	5.2	1.2	4.6
Content (%) 2008	43.3	22.6	0.6	24.8	6.7	1.5	0.5

was extinct in 2003. Nonetheless, despite the enormous mineralization, the Large Sea is still alive – some biological communities demonstrated high resistibility to the salinity growth. According to (Sapozhnikov et al., 2008), over 40 species of microalgae currently populate the Large Sea. The dominant specie in zooplankton is *Artemia parthenogenetica*, whose total stock in the Large Sea is as high as 50,000 t (Arashkevich et al., 2009).

The ongoing Aral Sea crisis also involves a variety of serious problems ranging from air pollution and deterioration of water resources to human health issues and significant challenges to the regional economy.

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Cross-references

Caspian Sea
 Classification of Lakes from Hydrological Function
 Water Balance of Lakes

ARCH DAMS, DEVELOPMENT FROM CUT-STONE ARCHES TO MODERN DESIGN

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Introduction

Dam designs may be divided into three main types: gravity structures relying on their weight for stability, arched structures using the abutment reaction forces, and buttress dams. Historically, the first dams were earthfill and rockfill embankments, for example, Sadd-El-Kaffara (Egypt BC 2800–2600), Marib (Yemen BC 750), Panda Wewa (Sri Lanka BC 400–300), Cornalvo (Spain AD 150–200). Masonry gravity dams were built at sites where good quality stones were available, for example, Khosr river (Iraq BC 694), Al-Harbaqa (Syria AD 132), Kasserine (Tunisia AD 100–200). Note that concrete and stone masonry dams are commonly called “gravity dams.” Sometimes, the dam wall was reinforced by masonry buttresses, for example, Alcantarilla (Spain BC 200–100), Proserpina (Spain AD 130). Later designs included arch dams, relying on the abutment reaction forces to resist the resulting water pressure force. A related design is the multiple-arch buttress dam, consisting of a series of arches supported by buttresses. Smith (1971) and Schnitter (1994) presented comprehensive treatises on the history of dams. However, the arch dam design was rare up to the late nineteenth century, and the historical development of such dams received less attention, with one notable exception (Schnitter, 1976).

The present contribution shows that the historical development of arch dams progressed during five periods: the Roman arch dams (First centuries BC and AD), the Mongol dams (fourteenth and fifteenth centuries), some advanced masonry dams in the early nineteenth century (1804–1856), the Australian concrete arch dams (1880–1896), and the modern arch shapes at the beginning of the twentieth century (1903–1928).

Terminology

It is inadequate to define a dam as curved or arched because it does not identify the relative importance of the gravity and the abutment forces in providing stability. Such a dam should correctly be called a curved-gravity, thick-arch or thin-arch structure. A *curved-gravity dam* is primarily a gravity structure relying on its weight for its stability, and the wall curvature adds little to its stability. By contrast, an *arch dam* would be unstable without the contribution of the abutment reaction forces.

A *thick-arch dam* relies both on its weight and on the abutment reaction for its stability. A *thin-arch dam* is a leaner structure relying predominantly on the abutment reaction forces for its stability; typically the ratio of the base thickness to the dam height (E/H) is less than one third. Practically, the arch dam design is well adapted to narrow gorges, and it produces substantial savings in costs compared to a gravity dam.

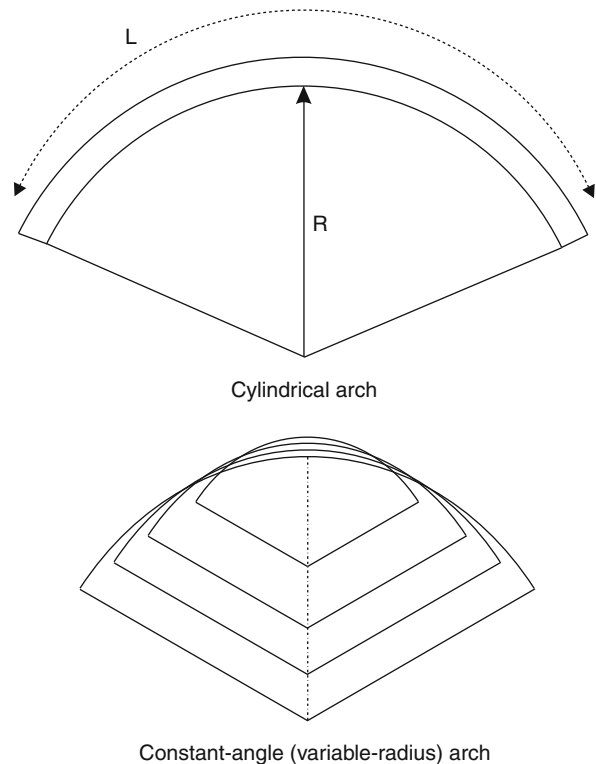
The basic arch dam shapes are the constant-radius arch, the constant-angle arch and the double-curvature arch with increasing complexity. The *constant-radius arch* design, also called the single-radius arch, is a cylindrical shape (Figure 1). The upstream face is usually vertical while the downstream face is battered. The *constant-angle arch* design is a variable-radius arch. The design is based on a constant central opening angle, with the arch radius increasing from base to crest (Figure 1). The concept was first introduced by Albert G. Pelletreau (1843–1900) in 1879 (Pelletreau, 1879). It results in considerable saving in construction material, compared to the constant-radius arch design. Lars R. Jorgensen (1876–1938) who applied the concept demonstrated that the dam contained minimum material for an optimum opening angle of 133.6° (Jorgensen, 1915); he added however that “the use of a smaller central angle [...] might be more economical, and 120° or even less [...] might give very satisfactory results.” The *double-curvature arch* design, also called spherical dome or cupola, has a more complex shape, and vertical curvature is introduced. The shell design results in saving in concrete but requires more technical skills than for a constant-angle arch dam.

Roman arch dams

The first arch dam is probably the Roman dam at Glanum, built during the first century BC to supply water to the Roman town (Table 1). The Roman dam was rediscovered in 1763 by Esprit Calvet (Benoit, 1935; Goblot, 1967). A recent study by Augusta-Boularot and Paillet (1997) indicated that the dam was made of cut stones held together with crampons and finished with waterproof cordon joints. The site was well selected, and the wall abutments were cut in the rock. A newer dam was built in 1891 at the same place, above the Roman dam foundation, and it still stands today. Another unusual Roman dam was the Esparragalejo dam, near Merida (Table 1). Built around the 1st century AD for irrigation purposes, the structure was a multiple-arch buttress dam, 5.6-m high and 2-m thick at base with circular arches.

Discussion

The Romans built gravity embankment dams (e.g., Alcantarilla, Spain BC 200–100; Proserpina, Spain AD 130), straight masonry gravity dams (e.g., Al-Harbaqua, Syria AD 132), and curved-gravity dams (e.g., Kasserine dam, Tunisia, AD 100? (Saladin, 1886), Çavdarhisar dam, Turkey (Schnitter, 1994)). But the dam at Glanum was unique. It was a slender thin-arch dam ($E/H = 0.265$). The authors hypothesize that the arch dam design



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 1 Comparative sketch of single-radius and constant-angle arch dams.

was introduced because the site was favorable to a masonry dam but nearby construction materials were scarce.

The arch technique was applied by the Romans to sewers, aqueducts and bridges, although there is no evidence of scientific design rules. Professor C. O'Connor suggested that, for Roman bridges, the ratio of arch rib thickness to span was about $1/10$ for spans less than 15 m and could be reduced down to $1/20$ for greater spans (O'Connor, 1993, pp. 168–169). Interestingly, the ratio of dam wall thickness to arch curvature radius was between $1/10$ and $1/7$ at Glanum, i.e., close to Roman bridge dimensions.

For completeness, some researchers (Schnitter, 1979; Augusta-Boularot and Paillet, 1997) suggested the existence of further Roman arch dams, e.g., Kasserine (Tunisia), Dara (Turkey), Çavdarhisar (Kütahya, Turkey), Örükaya (Çorum, Turkey). The Çavdarhisar and Örükaya dams were flood retention structures; their scour outlet system had cross-section areas of 11 and 3 m², respectively (Stark, 1957–1958). A reanalysis of these structures demonstrated that Kasserine, Çavdarhisar, and Örükaya were curved-gravity dams. In the particular case of Dara, the Byzantine historian Procopius (sixth century AD) indicated a curved dam, possibly as at Kasserine, and no remain is visible.

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 1 Characteristics of historical arch dams

Dam	Date	Design	Constr. material	H (m)	L (m)	e (m)	E (m)	R (m)	θ (deg.)	Remarks
Roman dams										
Les Peirou, Glanum (St-Rémy-de-Provence), France	First century BC	VA-b	Stone masonry	14.7	23.8	3.0	3.9	28.6	48	Town water supply. New arch dam built in 1891. (Authors' inspection (see also Chanson and James, 1998b); Agustá-Boularot and Paillet, 1997)
Esparragalejo, Mérida, Spain	First century AD	MV-CB	Stone masonry	5.6	320		2			Irrigation. Rebuilt in 1959. 12 buttresses (8.6-m span) (Schnitter, 1994)
Mongol dam										
Kebar, Qoum, Iran	AD 1300/1600	VA-a	Stone masonry	26 (1)		5 (1)	9 (1)	35 (1)	40 (1)	Gravity abutments. Fully silted dam still visible in the 1970s (Goblot, 1965, 1973)
Kalat-e-Naderi, Mashhad, Iran	AD 1350 (?)	VA	Stone masonry	26	74					Goblot, 1965, 1973
Kunit, Tabas, Iran	AD 1350/1850	VA-b	Stone masonry	60/64	27 (1)	1.2 (1)	15 (1)			Still visible in the 1980s (Schnitter, 1994; Goblot, 1965, 1973)
Chabb Abbasi, Tabas, Iran	AD 1400 (?)	VA	Stone masonry	20						Foundation washout without upper wall collapse (Schnitter, 1994; Goblot, 1965, 1973)
Early nineteenth Century dams										
Meer Allum, Hyderabad India	1804 (?)	MV-CB	Stone masonry	12	500			10.6–22.4	180	Designed by Henry Russle. Water supply. Still in use (Schnitter 1994; Smith, 1971; Engineering Record, 1903; Schuyler, 1909)
Jones Falls, Ottawa, Canada	1828–31	VA-a	Stone masonry	18.7	106.7	6.55	8.4	53.3		Designed by John by. Navigation and hydropower. Still in use (Legget, 1957–1959, 1972)

Zola, Aix-en-Provence, France	1847–54	VA-a	Stone masonry	24.5	66	5	13	48.2	77	Designed by Maurice Zola. Town water supply. Still in use for flood retention (authors' inspection (see also Chanson and James, 1998b); Schnitter, 1994; Smith, 1971; Coyne, 1930; Goblot, 1967)
Parramatta, Sydney, Australia	1851–56/1898	VA-a	Stone masonry/ concrete	12.5/15.8	80	2.3/1.46	4.6	48.8		Designed by P. Simpson, E.O. Moriarty & W. Randle. Town water supply. Still in use for recreation (Wade, 1909; Ash and Heinrichs, 1996)
Concrete dams										
75-M, Warwick QLD, Australia	1879–80/ 1900–01	VA-a/Buttress	Concrete	5.04/9 (?)	24.5/30	1.07/0.89	2.78	58.5	24	Designed by Henry Stanley. Railway water supply. Still in use (authors' inspection (see also Chanson and James, 1998b))
Lithgow No. 1, Lithgow NSW, Australia	1896/1914	VA-b	Concrete	10.7/11.5	54.3/55	1.07/1.1	3.32	30.48	102	Designed by Cecil Darley. Town water supply. Disused since 1986. (authors' inspection (see also Chanson and James, 1998b); Wade, 1909)
Junction Reefs, Lyndhurst NSW, Australia	1895–97	MV-CB	Concrete & bricks	18.3	131.4	0.5	1.22	8.53	180	Designed by O. Schulze. Hydropower for mining. five arches. Fully silted. (authors' inspection (see also Chanson and James, 1998b); Schulze, 1897)
de Burgh, Barren Jack NSW, Australia	1907–08	VA-b	Reinforced concrete	4.88	30.2 (?)	0.4		20.17		Designed by Ernst de Burgh. Railway water supply. Disused since 1929. Fully silted (authors' inspection (see also Chanson and James, 1998b))

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 1 (Continued)

Dam	Date	Design	Constr. material	H (m)	L (m)	e (m)	E (m)	R (m)	θ (deg.)	Remarks
Modern designs Ithaca, New York, USA	1903	VA-b cupola	Concrete & brick facing	9.1		0.3	2.4	17.6		Cupola designed by G.S. Williams to be 27-m high. Town water supply (Schuyler, 1909)
Hume Lake, California, USA	1908	MV-CB	Reinforced concrete	18.6	206.3	0.46	0.9	7.6	118	Designed by J. Eastwood. Fluming and logging pond. 13 buttresses (Wegmann, 1922)
Salmon Creek, Juneau ALSK, USA	1913–14	VA-b constant- angle	Reinforced concrete	51.2	199	1.83	14.5	45–100.9	113	Constant opening angle designed by L.R. Jorgensen.
Coolidge, Arizona, USA	1924–28	MV-CB cupola	Reinforced concrete	76	280	1.2	6.1			Hydropower. Still in use (Jorgensen, 1915) Cupola arches. Irrigation and hydropower. Modified in 1992–94. Still in use (Schmitter, 1994)

Notes:

Date: construction period (*underlined completion date*); 300/600: construction in 300, heightening in 600.

Design: VA = arch; VA-a = thick arch, VA-b = thin arch, MV-CB = multiple-arch buttress.

Notation: E : dam base thickness; e : dam crest thickness; H : dam height above foundation; L : arch dam crest length; R : radius of curvature of arch wall; θ : arch opening angle; (1) after first dam heightening; (?) : uncertain data.

Mongol arch dams

During the thirteenth century, the Mongols invaded and settled in Iran where they built several large dams, for example, the Saveh dam was a gravity dam built in AD 1285 ($H = 25$ m, $L = 65$ m). Around the fourteenth century, they built also some arch dams (Table 1). The Mongol arch dams in Iran had thick-arch walls, and they were significantly higher than the Roman dams. The first arch dam (Kebars, AD 1300) was heightened to 26 m around AD 1600, while the Kurit dam was 60-m high before heightening (Goblot, 1965, 1973). The Kurit dam was extraordinary, having the very-low crest length to dam height ratio L/H of 0.42 after heightening (probably less prior). It is interesting to note that these structures were used for several centuries. Several dams were still standing in the 1970s, although some were subjected to foundation failures, e.g., Chabb Abbasi. The complete upper portion of the dam wall was still standing in the 1970s despite the missing foundation (Goblot, 1973). In the authors' opinion, this highlights the soundness of the arch wall design and the quality of the masonry work. The Mongol dams were further equipped with sophisticated outlet systems (e.g., Kebars, Kurit).

Discussion

Some transfer of expertise on arch dam design might have taken place from the Romans to the Iranians. After the defeat of Valerian's army in AD 260, 70,000 Roman soldiers were captured and transported to Persia where they were forced to work. The Roman army was often involved in large-scale civil engineering works, in particular aqueduct constructions (Fevrier, 1979; Leveau, 1991), and it is likely that it was also involved in dam construction. The Roman prisoners built bridge-weirs and dams in Iran. Examples of bridge-weir include Dezful and Shustar, and an example of dam is Ahwaz (e.g., Smith, 1971; O'Connor, 1993; Schnitter, 1994). Shustar dam is also called Band-i-Kaisar or "Dam-Bridge of Valerian" (O'Connor, 1993). Ahwaz dam, also called Ahwaz weir, was a 900-m long masonry weir on Karun river. Some structures, for example, the Shustar bridge-weir, were still in use when the Mongols invaded in Iran. There is however no proof that the Mongols were aware of the Roman arch dams.

Both the Roman and Mongol dams in Iran were milestones in arch dam development. From the fourteenth century up to the beginning of the nineteenth century, the arch dam development was scattered and disparate. An arch dam was built in Italy at Pontalto in 1612, and the structure was heightened more than six times over the next 270 years from 5-m to 37.8-m. In Spain, Don Pedro Bernardo Villareal De Berriz (1670–1740), a Basque nobleman, designed and built one single-arch and four multiple-arch dams with vertical circular arches in the 1730s. They were low-head structures used for water power purposes, and four of them are still in good condition (Smith, 1971).

Masonry arch dams in the early nineteenth century

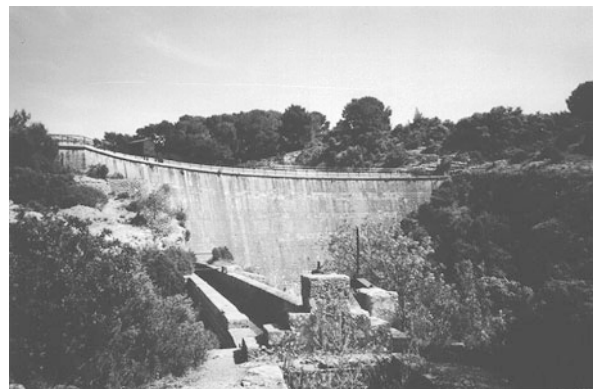
During the first part of the nineteenth century, the arch dam design was dominated by four large structures. These were the Meer Allum (India), Jones Falls (Canada), Zola (France), and Parramatta (Australia) dams (Table 1).

In India, Henry Russle, Royal Engineers, built the extraordinary Meer Allum (Mir Alam) dam with a 10-Mm^3 water storage capacity around 1804; see, for example, Engineering Record (1903), Schuyler (1909), Smith (1971), Schnitter (1994). The multiple-arch dam was built to supply water to Hyderabad, and it is still in use. It consists of 21 semicircular vertical arches with span ranging from 21.3 to 44.8 m.

In Canada, Lieutenant-Colonel John BY (1779–1836) built several curved masonry dams between 1827 and 1832 as part of the Rideau waterway system. One structure, the Jones Falls dam, was a true arch dam (Legget, 1957–1959; Smith, 1971; Schnitter, 1994). Completed in 1831, the 18.7-m high dam was a constant-radius arch wall, 8.4-m thick at base (Table 1). The dam is still used today for hydropower and navigation purposes.

François Zola (1795–1847) designed two arch dams in 1832 for the water supply of the city of Aix-en-Provence, France (Coyne, 1930, 1956). One, the Zola dam, was built between 1847 and 1854. It was the first arch dam design based on a rational stress analysis (Schnitter, 1994). The reservoir was used as a town water supply until 1877, and the dam is still in use for flood retention (Figure 2).

One of the first significant hydraulic structures in Australia was the Parramatta dam near Sydney (Figure 3, Table 1). Built between 1851 and 1856, the 12.5-m high arch dam was designed by P. Simpson (1789–1877), E.O. Moriarty (1824–1896), and W. Randle (Ash et Heinrichs 1996). It was a constant-radius arch with a cylinder shape, and it was heightened by 3.35-m in 1898 under the supervision of Cecil West Darley (1842–1928) (Wade, 1909).



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 2 Zola dam, Aix-en-Provence, France, in June 1998.



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 3 Parramatta dam, Sydney, Australia on September 27, 1999.

Discussion

All four structures were constant-radius arches built in cut-stone masonry. It is generally believed that the thickness of cylindrical arch was calculated using the thin cylinder formula because the concept was familiar at the time to engineers involved in shell and ship hull calculations.

It is worth noting that three dams were built in the British empire. Two structures were designed by Royal Engineers: the Meer Allum multiple-arch dam (1804?) and Jones Falls thick-arch dam (1831). It is possible that these designs influenced the Australian engineers with a transfer of expertise taking place through Royal Engineers. The Royal Engineers in India had a strong involvement in water supply systems, and they were sometimes called upon in Australia. The authors believe that the Royal Engineers in India were aware of the successes of Meer Allum and Jones Falls dams and they might have advised Australian engineers.

The four masonry arch dams are still in use for water supply (Meer Allum), hydropower (Jones Falls), flood retention (Zola), and recreation (Parramatta). Their long-lasting operation demonstrates the soundness of design and the quality of the masonry construction.

Concrete arch dams in Australia

Built near Warwick (QLD), the 75-miles dam was a water supply for steam locomotives (Chanson, 1999). The first dam was designed by Henry Charles Stanley (1840–1921). It was a concrete arch, 5.04-m high, 1.07-m thick at crest, and 2.784-m at the base. The dam was equipped with an overflow spillway, a scour outlet and a water outlet feeding a water tank located below beside the railway line. In 1900–1901, the dam was heightened to 8–10-m under the supervision of STANLEY. The enlargement included the addition of three concrete buttresses (Figure 4). The 75-miles dam in 1880 was the oldest concrete arch dam built in Australia, and possibly the world's oldest concrete arch dam. It was the second arch dam completed in Australia as well as the second dam built entirely of

concrete in Australia with a vertical upstream face and battered downstream face (1H:3.6V). The first concrete dam was the Lower Stony Creek dam near Geelong VIC completed in 1873 (Lewis, 1988; Harper, 1998).

Completed in 1896, Lithgow No. 1 dam was built as a town water supply and designed by C.W. Darley (Figure 5). The 10.7-m high dam was a concrete single-radius thin-arch structure with a vertical upstream face and battered downstream face (1H:3.6V). It was equipped with an overflow section and an outlet system. In 1914 or 1915, the dam was heightened by closing the spillway overflow section and adding new wing walls. A new overfall spillway was built. The dam was disused around 1983–84 because the reservoir did not have enough available head to feed the new wastewater treatment plant. It has been kept empty since 1986, and it is now used as a flood retention reservoir (Figure 5). Lithgow No. 1 dam was the first Australian thin-arch dam, and it is the world's oldest concrete thin-arch structure. The design by Darley became a standard, commonly called “Darley-Wade dam” design in Australia (Chanson and James, 1998b, 2002).

Between 1907 and 1909, Ernest Macartney de BURGH (1863–1929) built two thin-arch dams, de Burgh dam (1907–1908) and Barren Jack City dam (1908–1909), also called Barren Jack Creek dam, as part of the construction of the Burrenjack reservoir (Barren Jack NSW, 1927), also called Burrenjack or Barren Jack dam (concrete gravity structure, $H = 61$ m, $L = 233$ m) (Chanson and James, 1998b). First completed, de Burgh dam was built to supply water to the railway line supplying the construction site, also called Burrenjack or Barren Jack dam (concrete gravity structure, $H = 61$ m, $L = 233$ m). It was a reinforced-concrete single-radius thin-arch dam (Figure 6). The concrete wall was reinforced with 20-lb. rails, 1.52-m apart horizontally and 3.048-m apart vertically. The de Burgh dam was a true reinforced-concrete arch with rail reinforcement placed from toe to crest. The wall reinforcement was not a standard design feature of the Darley-Wade dams like the Lithgow No. 1 dam. With Hume Lake dam (see below), the de Burgh dam is the world's oldest reinforced-concrete thin-arch dam.

The oldest multiple-arch dam in Australia

Completed in 1897, the Junction Reefs dam is a multiple-arch dam, 18.3-m high (Figure 7). It was also called Junction Point Reefs dam or Belubula dam (Schulze, 1897; Schnitter, 1994). There are five elliptical arches, each with a 8.5-m span and a 60° lean. The dam foundation and outside walls were made of concrete while the arches and buttresses were built in brick. Brick construction was selected as the cheapest and quickest material to build for the arches, concrete being cheaper only for the foundation (Schulze, 1897). Curiously, the original design included six arches but the final design had only five arches because of delays in the brick-making. The arches were designed in the same way as bridge arches: “the arches were calculated in the same way as bridge [...] and the buttresses as



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 4 75-Miles dam (Warwick QLD, Australia). (a) View from downstream of the dam with the three concrete buttresses (Photograph taken on 23 January 1998). (b) Details of the dam crest and buttresses (Photograph taken on January 23, 1998).



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 5 Lithgow No. 1 dam (Lithgow NSW, Australia) (Photograph taken on January 26, 1998) View from upstream and right bank.



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 6 De Burgh dam (Barren Jack NSW, 1908) (Photograph taken in July 1998) View from right bank during a flood.

bridge piers” (Schulze, 1897, p. 171). Professor C. O’Connor commented that the arch shape and brick laying was unusual, the arch bricks being laid inclined parallel to the upstream arch face while the buttress elliptical shape was not easily understandable. Built to provide hydro-power for the nearby gold mine, the dam suffered heavy siltation and the reservoir is fully silted today. The design of Junction Reefs has been well known overseas (Wegmann, 1922; Smith, 1971; Schnitter, 1994).

Modern arch dam designs

The introduction of concrete as a construction material for arch dams marked a significant advance. Designers were able to consider complex curved shapes to minimize the construction material and the overall cost. The developments took place first in North America (Table 1).



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 7 Junction Reefs dam (Lyndhurst NSW, Australia) (Photograph taken on December 28, 1997) View from the left bank.

Professor G.S. Williams (1866–1931) designed the world's oldest cupola dam (Figure 8). The Ithaca dam (New York, USA, 1903) was designed to be a 27-m high structure, but construction was stopped when the dam height reached 9-m because of local opposition (Schuyler, 1909; Wegmann, 1922). An interesting construction detail was the brick facing used as concrete formworks.

The oldest concrete multiple-arch dam was designed by John S. Eastwood (1857–1924). The Hume Lake dam (California, USA 1908) was built in the Sierra Nevada Mountains in 114 days (Wegmann, 1922)! The 206-m long 18.6-m high structure consisted of 12 circular arches (15.24-m span) inclined at 58° with the horizontal and vertical in the upper 4.88-m section. The concrete reinforcement included old logging cables (over 12 km) and railroad scrap iron.

Lars R. Jorgensen designed the first constant-angle arch dam: the Salmon Creek dam (Table 1). (This is not strictly correct: Jorgensen (1915) mentioned a smaller constant-angle dam designed by an American H.F. Cameron in the Philippines around 1913–14. The 30-m high dam was used for Manila's water supply.) Completed in 1914, the Salmon Creek dam was 51.2-m high and the opening angle was 113° . The arch radius ranged from 44.96-m at base to 100.9-m at crest.

Another advanced design was the Coolidge dam (Globe Ariz., USA 1928). It was the first cupola-shaped multiple-arch structure. Consisting of three arches, it was designed and constructed by the US Bureau of Indian Affairs, and it is still in use for irrigation and hydropower.

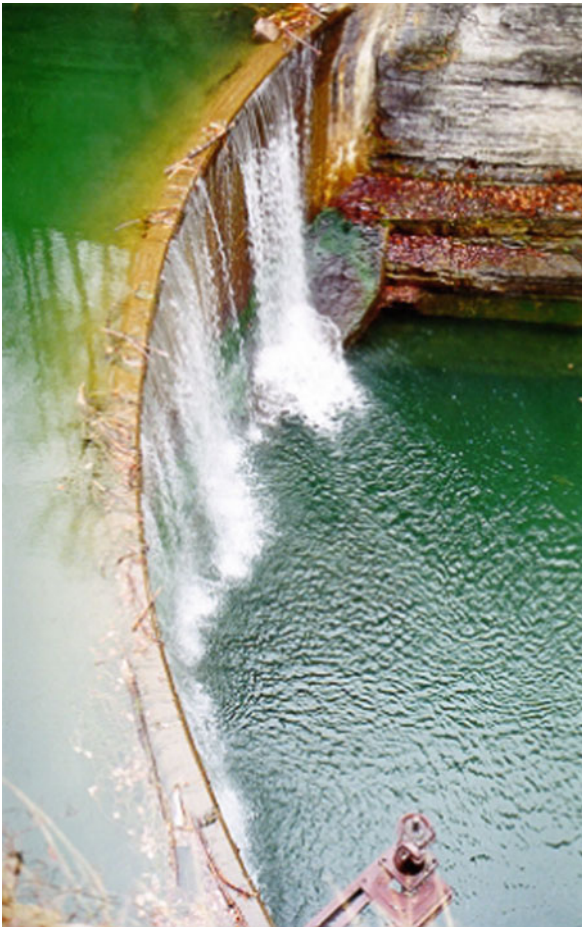
Discussion

Although dams were built as early as BC 3,000, and concrete was used by the Romans, the world's first concrete dams were completed in 1872 : Boyds Corner (New York,

USA) built between 1866 and 1872 and Pérolles dam (Switzerland) built from 1869 to 1872. The Boyds Corner dam underwent a major refurbishment in 1990, with the construction of a new spillway (6.1-m wide flip bucket in the central dam section) and the use of post-tensioned anchors to increase the dam stability. Also called La Maigrauge dam, the Pérolles dam was heightening in 1909.

These two dams were followed by others, e.g., Lower Stony Creek (Australia, 1873), San Mateo (San Mateo CAL, USA, 1888), also called Lower Crystal Springs dam. All these were gravity dams. In the United Kingdom, the first mass concrete dam exceeding 15-m in height was the Abbeystead dam completed in 1881 (Binnie, 1987). In Hong Kong, the Tytam dam, completed in 1887, was a concrete gravity structure with masonry stone facing. The Sand River gravity dam, completed in 1906, was the first concrete dam in South Africa (Schuyler, 1909; Wegmann, 1922). Note that the first South African arch dam was completed near Johannesburg in 1898–1899 for mining purposes. In India, the first large concrete structure was the Periar (or Periyar) dam built between 1888 and 1897 near Madras (Schuyler, 1909). In 1870, Rankine's opinion was sought as to the dam profile. In his reply, Rankine extended the method of de Sazilly and Delocre for the design of gravity dam, first applied to the Gouffre d'Enfer dam (Delocre, 1866; Rankine, 1872). This design method is considered as the basic analysis of the stability of gravity dams. Altogether, the construction of concrete dams began in the 1870s and intensified at the turn of the century.

Historically, after the Roman and Mongol era, the arch design fell out of favor until the nineteenth century. The development of arch dams was later facilitated by the introduction of concrete as a construction material.



Arch Dams, Development from Cut-Stone Arches to Modern Design, Figure 8 Ithaca dam (New York, USA), photograph taken in 1998 (Courtesy of Mr G. Toombes).

The world's oldest concrete thick-arch and thin-arch dams were single-radius arches built in non-reinforced concrete. The designs were based on the thin cylinder formula (Wade, 1909; de Burgh, 1917). The Australian concrete arch dam design was acknowledged in Europe and in the USA (Schuyler, 1909; Wade, 1909; Wegmann, 1922; see also Smith, 1971; Schnitter, 1994). Wegmann (in the discussion of Wade, 1909) stated that, in his opinion, "the curved dams built [...] in New South Wales had been designed more logically" than any other arch dams or curved-gravity dams.

Masonry construction: cut-stone or concrete

The zenith of stone masonry dam construction was the 1850–1900 period, and the construction techniques were well documented (Wegmann, 1893; Creager, 1917). Why did the Australian engineers select concrete as dam construction material? In Australia, concrete was used for waterworks, weirs, and dams as early as the 1870s. By world standards, large and innovative concrete works were produced such as the great dome of the Melbourne

Public Library (1908–1913) which was the world's largest reinforced-concrete dome at the time (Lewis, 1988). Concrete construction for arch dams was selected because of the lower cost, the facility of construction by unskilled labor and the ease to build irregular shapes compared to stone masonry construction.

Concrete was the cheapest construction material at the end of the century. Darley (1900) estimated the total cost of Australian arch dam at \$8 per m³ of masonry (Cost in US\$ of the time, with an exchange rate of about £ 1 = US\$ 4.9 (Schuyler, 1909)) (Table 2). Table 2 shows that the cost of concrete dam construction dropped from the 1870s to the 1900s and became lower than that of stone masonry. Darley's choice was consistent, although in advance, with world-known dam engineers. In 1909, Schuyler indicated that cyclopean concrete and mass concrete were both cheaper than rubble masonry and obviously cut-stone masonry for dam construction (Schuyler, 1909, p. 204). In 1922, Wegmann discussed the masonry type for gravity dams: "As far as strength is concerned cut stone would be the best class of masonry for building a dam, but, on account of its great cost, it is only used at the faces and for [...] ornamental work at the top." (Wegmann, 1922, p. 49). (This marked a change of opinion. In 1893, he stated that "rubble masonry is undoubtedly the best material that can be used for building a dam" compared to cut-stone masonry, concrete or rubble (Wegmann, 1893).) Interestingly, a brick construction was selected at Junction Reefs dam as being cheaper than concrete at this particular site.

Another advantage of concrete over cut-stone is the ease of construction by laborers and horse carts. At Lower Stony Creek, "owing chiefly to the scarcity of masons, [...] the dam was built of concrete instead of masonry" (Gordon, 1875, p. 402). Australian concrete dams were built of blocks of stone set in concrete, a technique called plum concrete or cyclopean concrete. "Plum stones to the maximum size that can be handled by two men" were used (Darley, 1900, p. 56). "All the concrete [was] mixed by hand [and] wheeled into place in barrows and trucks" (Wade, 1909, pp. 10–12). The concrete was laid in 3-ft courses "held between mould-boards [formwork] 10 ft long by 3 ft 6 in. high" (Darley, 1900, p. 55). By comparison, stone masonry necessitated a skilled workforce (i.e., stonemason artisans) and a plant to carry stones. For example, a machinery capable to carry 2–6 t was used to handle and place the masonry blocks at Parramatta dam (Figure 3, Ash and Heinrichs, 1996, p. 13). The ease of construction contributed to the lower cost but also suited well a new continent without skilled manpower.

A third advantage of concrete construction was the flexibility of shape: "With concrete [...] labour is saved and concrete has the farther advantage that it can be rammed into any irregular cavity" (Dobson, 1879, p. 111). Dobson referred to the construction of the Lower Stony Creek dam. Concrete offered a flexibility of shapes and curved designs (e.g., cupola shape). The introduction of concrete as a construction material paved the way for

Arch Dams, Development from Cut-Stone Arches to Modern Design, Table 2 Masonry dam construction costs

Dam	Year of completion	Dam type, masonry type	Masonry volume (m ³)	Masonry cost (US\$/m ³)	Remarks
Gouffre d'Enfer, Fra	1866	Gravity, Stone	39,986	8.0	
Lower Stony Creek, Aus.	1874	Gravity, Concrete	4,000	20.7	
Bear Valley, USA	1884	Arch, Stone	2,599	28.9	Located 1,890 m altitude
Betaloo, Aus.	1890	Gravity, Concrete	45,873	12.4	
La Grange, USA	1894	Gravity, Stone	30,200	18.2	
Williams, USA	1894	Gravity, Stone	3,996	13.2	
Junction Reefs, Aus.	1897	Multiple arch, Brick & concrete	5,352	10.0	Brick arches.
Seligman, USA	1898	Gravity, Stone	13,885	10.8	
Australian arch dams	1900	Arch, Concrete	–	8.0	Darley-Wade arch dams.
Barossa, Aus.	1902	Arch, Concrete	13,743	9.2	
Cataract, Aus.	1907	Gravity, Stone	111,810	14.3	
Cross River, USA	1910	Gravity, Stone	118,506	10.5	

Schulze (1897); Darley (1900); Schuyler (1909); Wegmann (1922); Harper (1998)

the newer modern designs : constant-angle and cupola arch dams, e.g., Ithaca (1903) (Figure 8).

The development of concrete dam construction under the leadership of Dobson and Darley marked the end of large stone masonry dam in Australia. From 1890, the highest large dam in Australia had been a concrete structure until the 1960s (Nimmo, 1966). An interesting parallel is the construction of masonry arch bridges. O'Connor (1974) showed that the construction of (notable) stone arch bridges came to a end basically in 1909. The historical development of bridges was characterized “by a complete cessation in the construction of major stone arches (c. 1909)” (O'Connor, 1974, p. 10). This date coincided with the construction of the Grafton bridge in Auckland (New Zealand) (completion 1910, 98-m clear span).

Multiple-arch dam design

The development of multiple-arch dams attracted some interest in Spain and Italy. Roman engineers built the oldest multiple-arch dam at Esparrageljo in Spain (Schnitter, 1994). In 1530, the architect Baldassare Peruzzi (1481–1536) proposed a multiple-arch dam for the reconstruction of a fishing pond reservoir in Siena, Italy (Schnitter, 1994, pp. 118–119). Turriano (1511–1585) recommended also the selection of multiple-arch dam “for use on large rivers” in his Codex (Garcia-Diego 1976). Villareal de Berriz built five multiple-arch buttress dams in Northern Spain around 1730.

In the nineteenth century, two significant structures were Meer Allum and Junction Reefs. Although Junction Reefs dam was smaller than Meer Allum, it incorporated new advanced features: elliptical arches and a sloping upstream face which enhances the dam stability. Further advances in designs were made with the Hume Lake and Coolidge dams.

Conclusion

The historical development of arch dams may be summarized in five stages (Table 1). The world's oldest

arch dams were built by the Romans in France and Spain. They were followed by the Mongols who built dams in Iran during the thirteenth and fourteenth centuries. However, it is not until the nineteenth century that significant progress in arch dam design was made. Four remarkable structures were the Meer Allum dam (India 1804), the Jones Falls dam (Canada 1831), the Zola dam (France 1854), and Parramatta dam (Australia 1856). All four of them are still in use today, and they demonstrated the soundness of arch dam design. Australian engineers pioneered the use of concrete as a construction material for arch dams. The world's oldest concrete arch dam was completed in 1880 : the thick-arch dam at 75-Miles. The world's oldest concrete thin-arch dam was the Lithgow No. 1 dam (1896). Both the 75-Miles and Lithgow No. 1 dams were made of non-reinforced concrete.

Modern arch dam designs were further developed in North America. The world's oldest cupola dam was completed in 1903 at Ithaca. The first constant-angle arch dam was completed in 1914. Modern multiple-arch design were completed in 1908 (Hume Lake) and 1928 (Coolidge). Since no major breakthrough has taken place. It is the writers' opinion that the introduction of concrete as construction material marked a major innovation in arch dam shape.

Notation

E dam base thickness (m)
e dam crest thickness (m)
H dam height above foundation (m)
L arch dam crest length (m)
R radius of curvature (m) of arch wall
θ arch opening angle

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ARCTIC LAKES

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Definition

Lakes located in an arctic area. Geographically it is the area north of the Arctic Circle, 66°30'N; climatically it is the area north of the 10°C isotherm for the warmest month, provided the mean temperature of the coldest month is below 0°C.

Arctic lakes may be classified according to the formation of the depression where the lake is formed and the material in the bottom of the lake. Many arctic lakes owe their existence to carving of the landscape by previous or recent glacial erosion. This erosion may result in numerous lakes of all forms and depths; however, often an orientation determined by the direction of the ice movement is seen. Elongated deeper lakes may be formed by the melt water (tunnel valleys). Other deep lakes may be formed by the melting of buried dead ice. In recent tundra areas, lakes may be formed by periglacial processes such as thermokarst and development of pingos. The material of the bed is most often till of variable thickness or solid bed rock. In recent glaciated areas, lakes may be formed at the margin between a glacier or an ice cap and the surrounding landscape. If the ice at the margin is melted or lifted because of buoyancy of the lake water; such lakes can be tapped very fast causing large floods, so called jökulhlaups. On larger glaciers and ice caps, lakes may be formed in depressions into the surface, so that the boundary consists solely of ice. Such lakes may interact with the drainage system of the glacier or the ice cap and may also cause severe floods if the melting in the bottom removes the sealing to the internal

drainage system. The thermal conditions of arctic lakes are characterized by mixing and layering caused by the density maximum of water at 4°C. Another characteristic pattern in arctic lakes is the formation of an ice cover that can last from a few days to perennial. The ice cover influences the light conditions and the heat budget of the lake and thereby the biological conditions. Depending on the bathymetry of the lake and the initial chemical composition of the lake water, the formation of ice can cause significant annual variations in the chemical composition. In the case of shallow lakes, the ice formation can cause formation of brine that again may precipitate and develop layered sediment on the bottom of the lake.

Shortly after the disappearance of ice cover, the lake water attains a temperature of 4°C. Warming by solar radiation and advection of warm air heats the water, with surface temperatures up to 10–15°C, while the deeper parts remain at 4°C. A stable layer called the thermocline is formed between the two water masses. In the autumn, cooling causes a new isothermic situation. Then further cooling leads to ice formation when the surface water temperature is close to 0°C. When the lake is ice covered the water temperature rises slowly because of solar radiation penetrating the ice and by thermal heating from the bottom. Deposition of snow diminishes the penetration of solar radiation and insulates the lakewater reducing the heat exchange.

Ice thickness in Greenland and Arctic Canada is 1.5–2 m, increasing from south to north; a maximum of 2.5 m is recorded on Ellesmere Island. Freeze up begins early to mid-September while breakup begins June to August. Lakes in high arctic can be covered by ice for several years, e.g., Romulus Lake on Axel Heiberg Island, but normally at least a moat of open water near the shore is formed. Examples of climatic arctic lakes in Canada are Baker Lake in Nunavut and Lac Klotz on the Ungava Peninsula, both south of the Arctic Circle. Examples of High Arctic lakes are found on the Canadian Arctic Islands. In Greenland, arctic lakes are situated on both sides of the Arctic Circle. Examples of saline arctic lakes are found near Kangerlussuaq, West Greenland, e.g., Braya Lake and Limnea Lake.

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Cross-references

[Ice Covered Lakes](#)
[Lake Ice](#)
[Thermal Regime of Lakes](#)

ARTIFICIAL WETLANDS

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Definition

An artificial wetland is a wetland constructed by humans. It consists of a water body that has a water table above or near ground level, which is to a large extent covered by vegetation.

Since artificial wetlands are created, they differ from wetlands which are made through restoration or developed in a natural process. The difference between a created and a restored wetland is not obvious since restored wetlands also include those that historically have been diked out through draining in order to make space for agricultural land. These wetlands can be restored relatively simply by stopping or significantly decreasing the drainage. Thus, what many laymen regard as a created wetland is in many cases actually a restored one. In other words, if a wetland has existed at the place within the past 100–200 years, the present wetland is a result of restoration.

There are various ways of describing the difference between a wetland and a pond. From an engineering perspective, the difference is the quantity of vegetation, as a pond has minor vegetation while the opposite is true of a wetland (see [Urban Lakes and Ponds](#)). Size is unimportant, however, and may range from only a few square meters to several hectares. It may be added that systems such as infiltration beds and detention ponds are not considered to be artificial wetlands.

The main purpose of artificial wetlands is always to create added value for humans. Their function may be to purify water, reduce flooding, and increase the biological diversity. It may also be the case that an artificial wetland has arisen in connection with earlier industrial activity such as fish culture. Today, artificial wetlands are most often used as biofilters in order to purify wastewater from industries (such as dairy farms or pulp mills) and households, and also to treat leachate water from landfills. The increased focus on water purification by artificial wetlands has mainly been due to the fact that vegetation generally supports the purification, which makes them more effective than ponds. If the primary aim is to create a beautiful water body in a park, ponds are laid out more frequently than wetlands since one normally does not want to have too much vegetation. The same is true if the focus lies on creating a larger water volume for irrigation, as this results in a deeper pond that counteracts the establishment of vegetation.

Water entering a wetland may come from ground water, streams, swales, or pipes. The water is then either transported over ground level (i.e., surface-flow wetlands) or through the soil (i.e., subsurface-flow wetlands). In the

latter, the water is transported horizontally or vertically (i.e., vertical-flow wetlands). Generally, water entering vertical-flow wetlands is dosed or poured from the surface, however, it may also be applied from the bottom and then transported to the surface.

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Cross-references

[Urban Lakes and Ponds](#)

ASIA, LAKES REVIEW

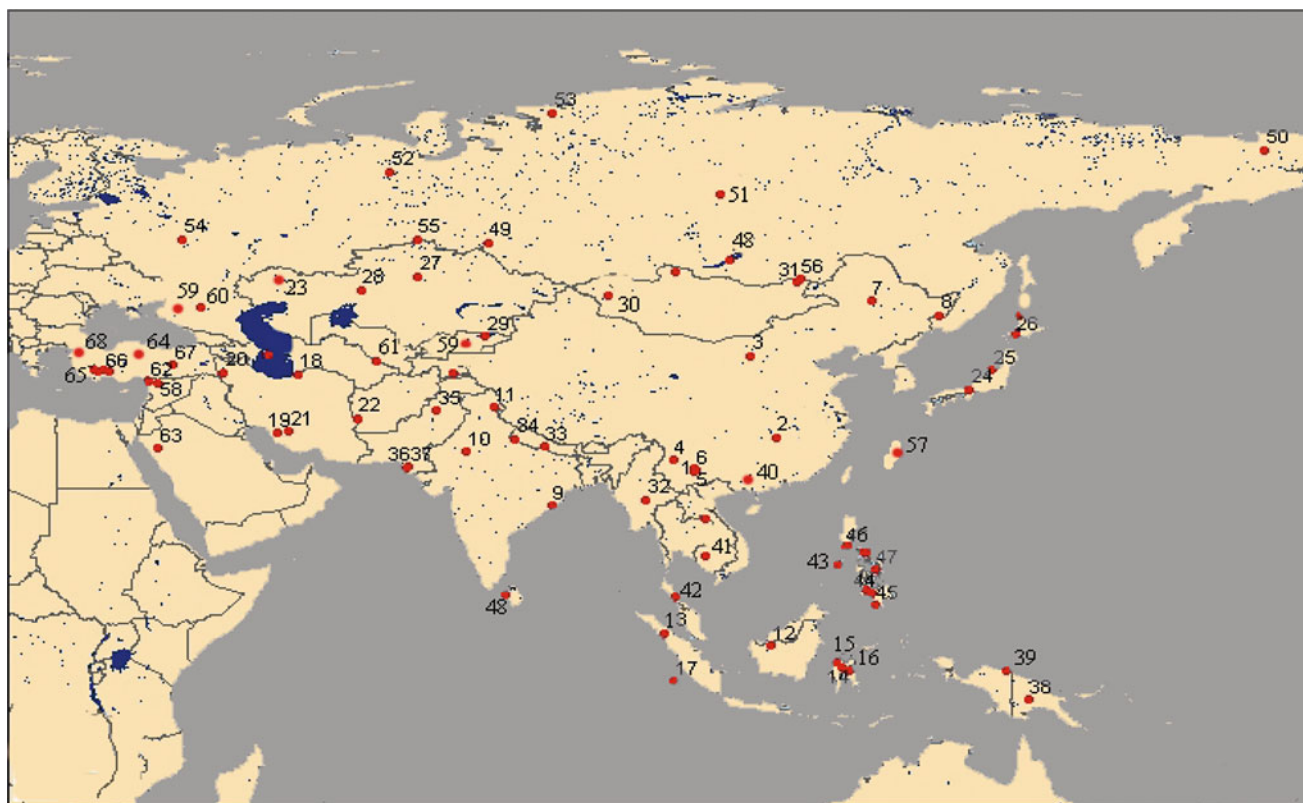
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Introduction

Asia has a total land area of 45,036,492 km² (17,388,686 square miles), not counting small islands, extending from the Arctic Ocean at about 77° 45'N to the East Indies (Indonesian Archipelago) at Roti Island, in the southern hemisphere (10°20' S), and from Asia Minor in the west (26°04' E) to the Bering Straits 169°40'W. Its principal W boundary is the Ural Mountains and Ural River to the Caspian Sea. The eastern limit of the Indonesian archipelago is generally taken to be the international boundary, Irian Barat and Papua New Guinea (141°E). The highest mountain in Asia (and the world) is Mt Everest, 8,848 m (29,028 ft), part in Nepal, part in China (Tibet). Its longest river, the Yangtze-Kiang (Chang Jiang), is 6,380 km (3,964 miles). (Geographical Information: *The Times Atlas of the World* (Bartholemew, 1999), 10th ed.)

Of the 18 major natural lakes in Asia, in terms of area, only one is located in the wet tropical zone, none in the arid, high-pressure belt, none in the subpolar arctic region, and only two in the Alpine–Himalayan orogenic belt. As a result, almost all the rest are to be found in the complex of block-faulted forelands, the central Asian orogenic systems and their intramontane depressions. Some of the smaller lakes are related to the strike-slip structures of the Middle East (Dead Sea, Galilee, etc.) or to the fluvial overflow associated with major rivers that include the Tigris, the Volga, the Amu-Dariya, and those of Siberia and China ([Figure 1](#)).

Two areas are covered with a peppering of very small endorheic drainage systems and isolated lakes, each of different origins though both are inherited from the last



Asia, Lakes Review, Figure 1 Distribution of Lakes in Asia (after LakeNet). 1, Dianchi; 2, Dongting; 3, Eerdudsi; 4, Er Hai; 5, Fuxian; 6, Xingyun; 7, Zhalong; 8, Xingkai; 9, Chilika; 10, Sambhar; 11, Tsomoriri; 12, Sentarum; 13, Toba; 14, Poso; 15, Lindu; 16, Malili; 17, Triton; 18, Alagol Umagol; 19, Parishan; 20, Umia; 21, Neiriz; 22, Sistan Basin; 23, Caspian; 24, Biwa-Ko; 25, Sakata; 26, Utonai-Ko; 27, Kutcharo; 28, Kourgaldzhin and Tengiz; 29, Turgay and Irgiz; 30, Issyk-kul; 31, Mongol Daguur; 32, Inle; 33, Beeshazar; 34, Ghodaghodi; 35, Chashma; 36, Haleji; 37, Kinjhar; 38, Murray; 39, Bato; 40, Kutcharo; 41, Parapolsky; 42, Songkhla; 43, Laguna De Bay; 44, Lanao; 45, Sebu; 46, Taal; 47, Twin Lakes; 48, Annaiwilundawa Tanks; 49, Baikal; 50, El' Gygytyn; 51, Hovsgol; 52, Dvuobje; 53, Pura and Mokoritto; 54, Oka and Pra; 55, Tobol-Ishin; 56, Torey; 57, Poyang; 58, Sabkhat Al-Jabbul; 59, Kuban Delta Limans; 60, Manych Guildio; 61, Dengizul; 62, Amik; 63, Bafa; 64, Beysehir; 65, Burdur; 66, Ergidir; 67, Hazar; 68, Kus.

glacial phase of the Pleistocene. The one is on the interior plateau of Tibet which is a very dry area in the rain shadow of the Himalayas to the S. and the Kun Lun to the N. The other is the tundras of N. Siberia where there is deep permafrost, which periodically melts near the surface and thus generates small lakes.

Finally, two lake systems must be characterized as unique:

- The Caspian Sea, which is a compound of an orogenic foredeep depression and an interior basin, also representing the largest inland body in the world
- The Tonlé sap, which has the remarkable characteristic of being filled by flow from the Mekong R. when the latter is in flood, and then reversing its flow during the dry season when the Mekong is low

Meteorologically, Asia is dominated by the seasonal alternation of the winter season when snow accumulation over Siberia and Tibet leads to a quasi-permanent high-pressure system that generates northerly winds in the Middle East, India, and NE airflows in China and the

East Indies. The latter become warmed in the tropics and eventually pass into the southern hemisphere as the wet NE Monsoon of the East Indies and northern Australia. In the summer season, this high pressure is replaced by low pressure systems that create the inward directing Asiatic Monsoon from the tropical part of the Indian Ocean. This brings the familiar wet Monsoon of India and S.E. Asia.

Besides the monsoon alternations there is the seasonal shift in prevailing westerlies and their jet streams. The winter flow brings the seasonal rains at the beginning of the year into the Middle East, Israel, Syria, Turkey, and Iraq, sporadically reaching as far as northern India. With summer, the jets weaken but may swing across northern Europe to northern Scandinavia and rarely touch northern Asia.

Natural lakes, geomorphic divisions

Epeirogenic basins and plains

- Caspian Sea*, the world's largest inland water body, is divided between Europe and Asia, and is partly in the Russian federation, Kazakhstan, Turkmenistan, Iran,

and Azerbaijan. It is 1,220 km (760 miles) in length, N-S. It covers 271,000 km² but is increasing today. The water is the so-called "caspi-brackish," that is, not salty like the ocean with its dominance of NaCl, but with NaSO₄ (and other salts). Its primary intake is from the Volga which drains central Russia but has no outlet at the present time. During the Pleistocene cold cycles, at times, its level rose to form a spillway in the Manych Depression north of the Caucasus to debouch into the Black Sea. Its total drainage area is 3,100,000 km² and capacity is 78,200 km³, having a maximum depth of about 1,025 m (3,363 ft), with a surface elevation about 28 m (92 ft), but it fluctuates considerably, rising at the present time due to increased rainfall in the intake areas.

Its marginal areas are marked by very considerable petroleum reserves, those around Baku (Azerbaijan) being amongst the oldest to be exploited. Newer discoveries mark the borders of Kazakhstan. Another economic product is the caviar, obtained from the sturgeon caught in the Volga estuaries, and also from Iranian sources.

On the eastern side (Turkmenistan) is a wide shallow embayment, the salty Zalif Kara-Bogaz Göl, some 160 km wide, separated from the main body of the Caspian by a long spit, but connected at the N end by a narrow channel. This Kara-Bogaz Gulf has long been famous for its remarkable salt accumulations.

2. *Aral Sea*, is situated partly in Kazakhstan, partly in Uzbekistan, and once placed as the second largest water body in Asia, formerly fourth largest in the world. In Roman times, it was known as *Oxianus Lacus*. Its area was 67,000 km² (26,000 square miles). It was 450 km (280 miles) long. However, during the mid-twentieth century, its intake waters were severely curtailed by irrigation dams on the Syr Darya and Amu Darya and also by persistent droughts. As a result, its volume was reduced by about 90% by the beginning of the twenty-first century. A large fishing industry was destroyed.

Discoveries in the early twentieth century by Ellsworth Huntington the American explorer showed that the Amu Darya formerly flowed into the Caspian, but climate changes and drifting sands from the Kyzylkum Desert blocked its Caspian channel and established the Aral Sea connection, now interrupted once more.

3. *Kaludinskoye Ozero*, located 300 km SW of Novosibirsk, in the wide Kulundinskaya Steppe. Covering about 728 km² (280 square miles), it has no outlet and is quite salty. It is about 190 m above sea level.
4. *Chany Ozero*, in the NW Novosibirsk Oblast, located 250 km E of Omsk and 20 km S of Chany station on the Trans-Siberian Railway. It occupies a slight depression in the wide Barabinskaya Steppe. The lake is about 2,500 km² (965 square miles), at an elevation of about 180 m. It is fed by streams from swampy arms to the east but has no outlet.

Structural depressions

1. *Lake Baykal (Baikal)*, situated in the Buryat Republic of southern Siberia, covers 31,500 km² (12,162 square miles), being 635 km (395 miles) in length and has a remarkable depth of 1,620 m (5,313 ft), with a 31,500 km³ capacity, which makes it the largest freshwater lake in Asia, sixth largest in the world, and the deepest in the world. Its intake flow is by the Berguzin R. and Selenga R. on the east side and the Upper Angara from the N. Its outlet is in the S.W. to the Angara proper (on Upper Tunguska). It was discovered by Russian explorers in 1643. The lake is frozen in winter. Its biota, including seals related to Arctic and Caspian forms, is marked by many Arctic marine fauna, which suggest marine connections at least in the Miocene or even earlier. Climatologically, Lake Baykal plays an important moderating effect on the otherwise extreme continentality of the region. Deep drilling in recent years has disclosed a long history of climate changes in the lake and its environments.
2. *Hövsgöl Nuur* (göl = lake in Azeri language; nuur = lake in Mongolian) is located in northern Mongolia about 250 km WSW of Lake Baykal, to the S of the Sayan Range. Hövsgöl (also known as Kosogol) covers 2,620 km² (1,010 square miles) and is about 1,713 m (5,620 ft) above sea level. Mountains to the N reach 3,492 m, and the E 2,396 m (5,620 ft). It has an outlet in the S by the Egiyum Gol which connects to an extensive network to the east.

Intermontane basins

1. *Lake Balkhash* (Ozero) is a partially salt lake in eastern Kazakhstan, fed by the Ili R. and others in the east, but lacking any outlet. Its southwestern part is largely swamp. Near the mouth of the Ili R., it is almost fresh, salinity increasing toward the E where there is a modest salt industry. There is also commercial fishing. It covers 19,140 km² (7,115 square miles) and measures 605 km (376 miles). Remarkably shallow, 26 m (85 ft), its capacity is only 18,200 km³.

It is hemmed in to the N and NW by the Kazakh Hills but appears to have been progressively constricted by growth of the Sary-Ishik-Otran Desert with its alluvial fans and dunes emanating from the Djungurskiy Alatau Mountains that mark the border of western China. The east end of the lake shows connections with a string of smaller lakes including L. Alakol (see below).

2. *Khanka Ozero* (Hsing-kai Hu, in Chinese) is situated across the China-Russia border, some 200 km N of Vladivostok. It is in the Primorski Krai of Russia (about three quarters). Covering about 4,400 km² (1,700 square miles), it is 88 km long (55 miles), and 10 m (33 ft) deep. Its waters are fresh, with an outlet on the E into the Ussuri R, which forms the international boundary, flowing N to join the Amur near Khabarovsk.

3. *Lop Nor* (Lo Pu No Erh, in Chinese) is a shallow salt lake, marshy in part, at the E end of the Tarim Basin of western China (Sinkiang Uighur). It is about 3,500 km² (1,350 square miles) and is fed by the Tarim River, the course of which has changed somewhat through history, following the N. border of the Taklimakan Desert (Shamo). The lake is normally about 60 km long but, in wet cycles has expanded to 400 km. This was the former "North Route" of the famous "Silk Road" from China to the West, the routes matching the climate cycle.
4. *Uvs Nuur*, a lake in NW Mongolia at the foot of the Tannu-Ola Range that borders Siberia. It is 3,350 km² (1,295 square miles) and about 2,500 m above sea level. Marked by endorheic drainage, it is clustered with some smaller interconnected lakes, Har-Uus Nuur, Har Nuur, Döröö Nuur, and Hyargas Nuur (1,480 km²), all lying N of the Altai Mts.
5. *Alakol Ozero*, situated in Kazakhstan, E of Lake Balkhash in a chain of small lakes (including Sasykkol). It covers 2,650 km² (1,025 square miles). Elevation is about 1,700 m (5,575 ft). It is bounded to the S by the Dzhungarskiy Alatau Range and to the N by the Tarbagatai Range.
6. *Ebinur* (Ai-pi Hu in Chinese), a salt lake in western China near the border of Kazakhstan. It is situated at the W end of the Junggar Pendi (Basin) and appears to be the SE member of a chain of lakes starting with L. Balkhash, separated by a narrow pass in the Djungarian Alatau known as the Djungarian Gate. It is bounded on the S by the Borohoro Shan, a branch of the Tien Shan, which provides meltwater streams that feed the lake in summer. Its areal dimensions vary seasonally, up to 1,420 km² (550 square miles), at less than 200 m above sea level.
7. *Qinghi Hu*, a salt lake in an endorheic depression N of the Qinghi Nanshan range, and E of the Qaidam Basin. It is about 100 km long and covers 4,220 km² (1,625 square miles). Its depth is 38 m (125 ft) at an elevation of 3,205 m (10,515 ft). It is fed by streams from the NW (Datung Shan), notably the Buh He.
8. *Bosten Hu*, about 3,000 km² (1,160 square miles) and situated in a trough between two branches of the Tien Shan, to the N of the Tarim Basin. It has no outlet, but is fed by streams from all sides, notably the Kaidu He from the west.
2. *Lake Urmia* (or Urumiyeh; Shahi in Persian; also *Lake Rezaïyeh*; or *Matianus*, in ancient literature). Located in NW Iran, it is a shallow, saline lake, E of Rezaïyeh and W of Tabriz. Its area is about 4,700 km² (1,815 square miles), about 145 km (90 miles) long, and about 15 m (50 ft) deep. Shahi Island is in the middle. The lake is about 1,297 m (4,353 ft) above sea level. It is fed by the Talkheh R. from the NE and the Elborz Mts., and by the Zarineh R. from the SW, and the Zagros Mts. It has no outlet and is thus hypersaline (about 23% salt), but it varies greatly with the seasons. It cannot support normal lacustrine life. Thanks to a deep boring, it has been studied geologically by a German team.
3. *Lake Van* (*Van Gölü*, the latter meaning salt lake in Turkish; *Thospitis* in ancient times) is situated in eastern Turkey in the Armenian "knot" between the Taurus Mts to the S and Süphon Dag (4,058 m) to the N. It has an outlet in the W to the Bitlis R, a tributary of the Tigris, with several small feeders from the E and S. The water is brackish. Formerly, it fed into the Euphrates, but the outlet was blocked by the lavas of a volcano. It covers 3,760 km² (1,919 square miles), about 128 km (80 miles) long, and about 25 m (82 ft) deep. Its elevation is 1,720 m (5,643 ft).

Fluvial floodplain

1. *Tonlé Sap* (Grand Lac, in French) is a quite remarkable water body, in western Cambodia, that is linked by a reversible channel to the Mekong River which runs to the W, filling the lake when the Mekong is in flood, but to the E at other times. Its outlet is at Phnompenh. At its maximum state, it covers 6,475 km² (2,500 square miles). The celebrated Buddhist temples of Angkor (of the Khmer people) are at the W end of the lake, but were inundated periodically during the Middle Ages and deeply buried by 3–7 m in sediment.

Reservoirs and man-made lakes

As may be expected for a continent with broad expanses of desert and vast numbers of small endorheic drainage systems, Asia possesses an extraordinary number of reservoirs and other man-made water bodies. Ancient civilizations led the way in China, India, and the Middle East.

In China, major engineering work was applied to the Yellow River (Hwang Ho) which is 4,671 km (2,903 miles) in length. It normally debouches into the Gulf of Chihli in the Yellow Sea (Bo Hai), but has been periodically shifted to a system of lakes and canals to join up with the Yantze Kiang at Nanjing. The most recent engineering undertaking has been the Three Gorges dam which is probably the world's largest.

In India, in the time of the British "Raj," there were extensive modifications to the upper tributaries of the Indus, mainly for irrigation purposes. Here, the earliest

Orogenic trough

1. *Issyk Kul* (köl), a brackish lake in N.W. Kyrgyzstan, separated from Kazakhstan on the N by the Kungei Alatau and from Western China in the S. by the Tien Shan Mts. It covers 6,200 km² (2,394 square miles) at an elevation of 1,609 m (5,279 ft). It measures 185 km (115 miles) in length and 98 km (38 miles) across. Depth is 702 m (2,303 ft). From time to time, it receives water from the Chu R. at the W end. It has no outlet and sits in a rain shadow of over 6,000 m mountains.

operations were about 5,000 years ago by the Harrapan people to provide urban supplies to the city of Mohenjodaro.

In modern Iraq (ancient Babylon, Assyria, Sumaria, etc.), the Tigris (1,890 km, 1,180 miles long) and the Euphrates (3,597 km, 2,235 miles) run more or less parallel, but in ancient times, its lower course lay farther to the west and large lakes were created. Both rivers have been dammed in the Turkish area and long reservoirs created.

In Yemen, there was a famous dam that collapsed during an earthquake in the fifth century AD, which led to great social distress. In modern Israel, extensive use of the Jordan water and salt exploitation of the Dead Sea have also created problems.

Cross-references

[Indian Lakes](#)

[Japanese Lakes](#)

AUSTRALIA, CLIMATE AND LAKES

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Introduction

Australia is an aged, flat continent. With the exception of the Eastern Highlands, especially in North Queensland and in areas of the Snowy Mountains in New South Wales and Victoria, there is little terrain. Lakes tend to be shallow and often ephemeral. Two well-known examples are Lake Eyre, in South Australia, and Lake George, outside Canberra ([Figure 1](#)). Lake Eyre is famous for its spectacular wildlife explosions during the rare occasions when standing water is available. Lake George is well known for its paleoclimatic and paleolimnology information (Timms, [1992](#)). These and many other lakes will fill under high rainfall and runoff conditions. Except for coastal lakes, total water evaporation often occurs in drought conditions.

General climatic features

The Australian continent is mainly located under the descending branch of the tropical (Hadley) circulation cell. Subsidence creating dry warm air encourages dry conditions at the surface. More than two-thirds of the continent receives less than 500 mm per year of rainfall. The age and terrain of Australia provide limited influences on atmospheric circulation (Bridgman, [1987](#), [1998](#); Hobbs, [1998](#)). [Figure 2a](#) and [b](#) shows a simplified synoptic climatology for Australian winter and summer conditions. Autumn and spring are transition seasons. In winter

([Figure 2a](#)), the northern two-thirds of the continent is under the influence of the southeast trade winds. This is the dry season of the year for the north, with the only major rainfall from orographic process on the Eastern Highlands in coastal Queensland. The geographical center of the anticyclonic movement is from 30°S to 33°S. Farther south, frontal and cyclonic (hurricane) activity associated with the circumpolar westerlies dominates, creating the winter season of maximum rainfall in the Perth area, southeast South Australia, Victoria, Tasmania, and southern New South Wales. Cold fronts linked to lows located south of the Great Australian Bight often extend north of 30°S, but rainfall is sporadic from these systems.

In contrast, summer circulation is more complex ([Figure 2b](#)). The center of anticyclonic movements shifts south to between 38° and 40°. This change allows onshore circulation patterns in the southern half of the continent. Sea breezes and mesoscale frontal systems occur regularly in coastal zones (Sturman and Tapper, [1996](#)), with the latter bringing moist air onshore. A combination of orographic and convective processes creates a summertime maximum in rainfall in New South Wales and Queensland. In the north, the Australian “monsoon” is usually active. The two major heat lows (Pilbara in Western Australia; Cloncurry in Queensland) are instrumental in encouraging the Intertropical Convergence Zone to move into the northern part of Australia. Moist, hot northwesterly winds follow, creating major rainfall between late November and early March. [Figure 3](#) provides a contrasting summary of rainfall and climatic zones for the Australian continent.

Late summer to early autumn is also the tropical cyclone season (Bridgman, [1998](#)). On average, eight to ten cyclones can form in the warm seas adjacent to both the northwest and northeast coasts of Australia. About half reach landfall, often after recurving in southerly direction from initial westerly tracks. When they move inland, the associated heavy rainfall can result in severe flooding, which carries to southern parts of the continent through swollen river systems. During these periods, the lakes are normally full of water, and wildlife moves inland from the coast.

Climatic variations

Variations to this general climatic pattern bring the extreme periods to Australian climate which are well known to the population. Particularly significant are extended periods of drought, high temperatures, and high variability of rainfall. It is not usual for a long period of drought to be broken by a period of heavy rainfall, replacing dry landscapes with floodwaters.

Much of these variations in eastern Australia can be attributed to changes in pressure between the western and eastern Pacific. This difference in pressure is calculated on a daily or monthly basis through the Southern Oscillation Index (SOI) (see Hobbs, [1998](#); Sturman and Tapper, [1996](#) for useful summaries). There is a significant



Australia, Climate and Lakes, Figure 1 Map of Australia showing the larger relief features and the location of lakes described in the text (Drawn by Olivier Rey-Lescure, University of Newcastle, NSW, Australia).

correlation between SOI, and variations in diurnal temperature range, precipitation, and cloud cover over much of eastern and northern Australia (Bridgman, 1998). When the SOI is average or positive (La Niña), convective conditions leading to normal to high summer and autumn rainfall in northern and eastern Australia prevail. During these times, river flow is high and most lakes are full of water. When the SOI is negative, the pressure variations between the eastern and western Pacific reverse, creating an El Niño situation. Drought conditions in much of eastern Australia can prevail, depending on the strength and duration of the El Niño event, and many lakes dry up.

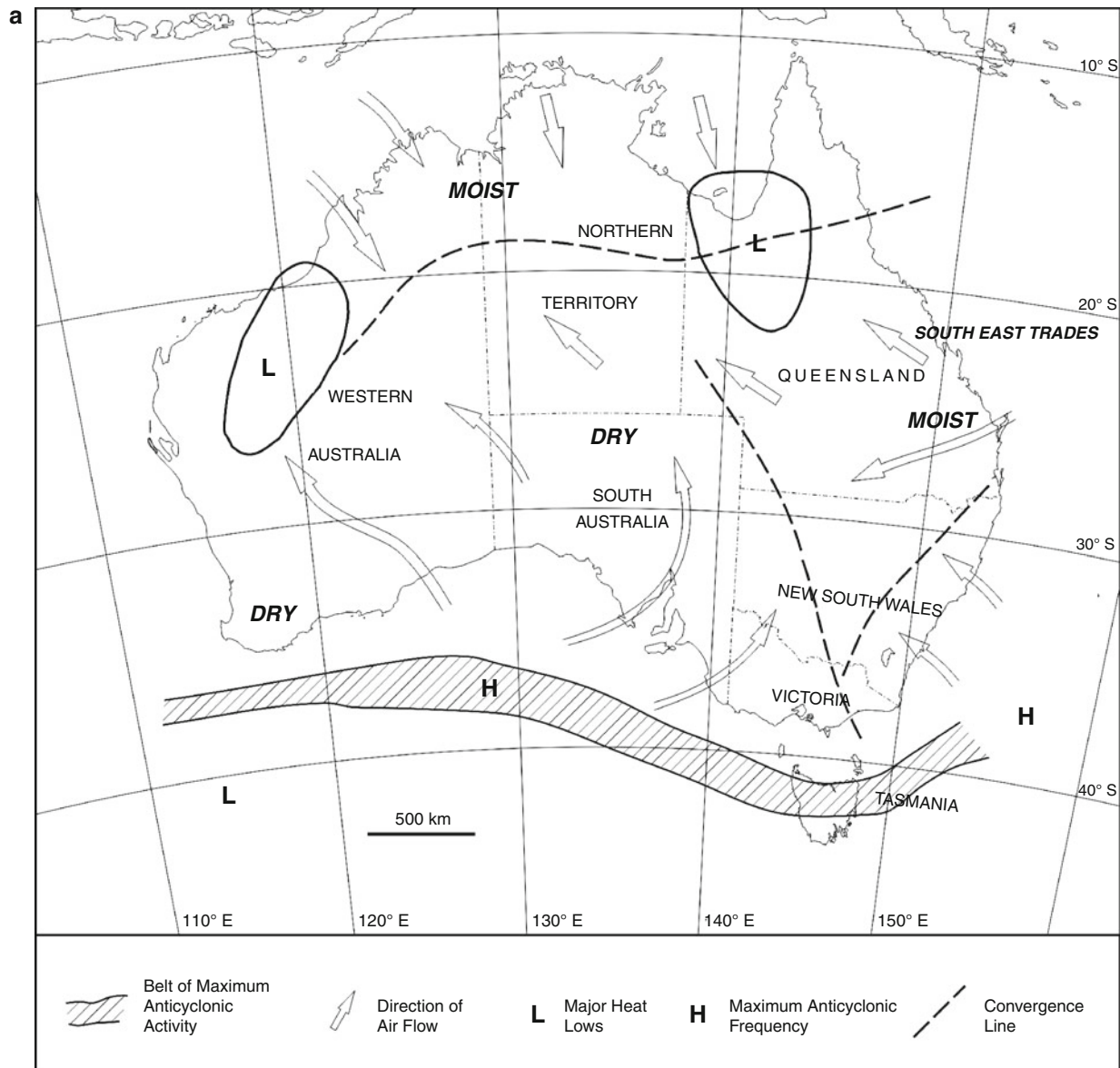
Hobbs (1998) emphasizes that the Southern Oscillation has an imperfect relationship with Australian rainfall, indicating that other factors are important. For example, rainfall amounts are strongly linked to sea surface temperature (SST), which can vary for other reasons besides the SO. While warm SSTs can lead to heavy rainfall, and cold SSTs the opposite, the impacts can be very complex

and result in a mix of wet and dry areas depending on geographical location.

Another important feature that influences Australian climate is the circumpolar westerly circulation around Antarctica (Karoly et al., 1998). Waves in this circulation pattern in the mid- to upper troposphere are divided into two types: those that are relatively stationary over long periods of time (Waves 1, 2, and 3) and those that are smaller and are transient over time (Waves 4, 5, and 6). Waves 1 and 3 affect the interaction in airflow from Antarctica to Australia the most, especially over the western half of the continent. Small shifts in the location of these stationary waves from season to season can have major influences on rainfall and temperature variations over Australia.

Lakes in Australia

On a world scale, Australia has relatively few lakes, which is not surprising given that 39% of the continent is arid and another 39% semi-arid. Nevertheless, maps show many

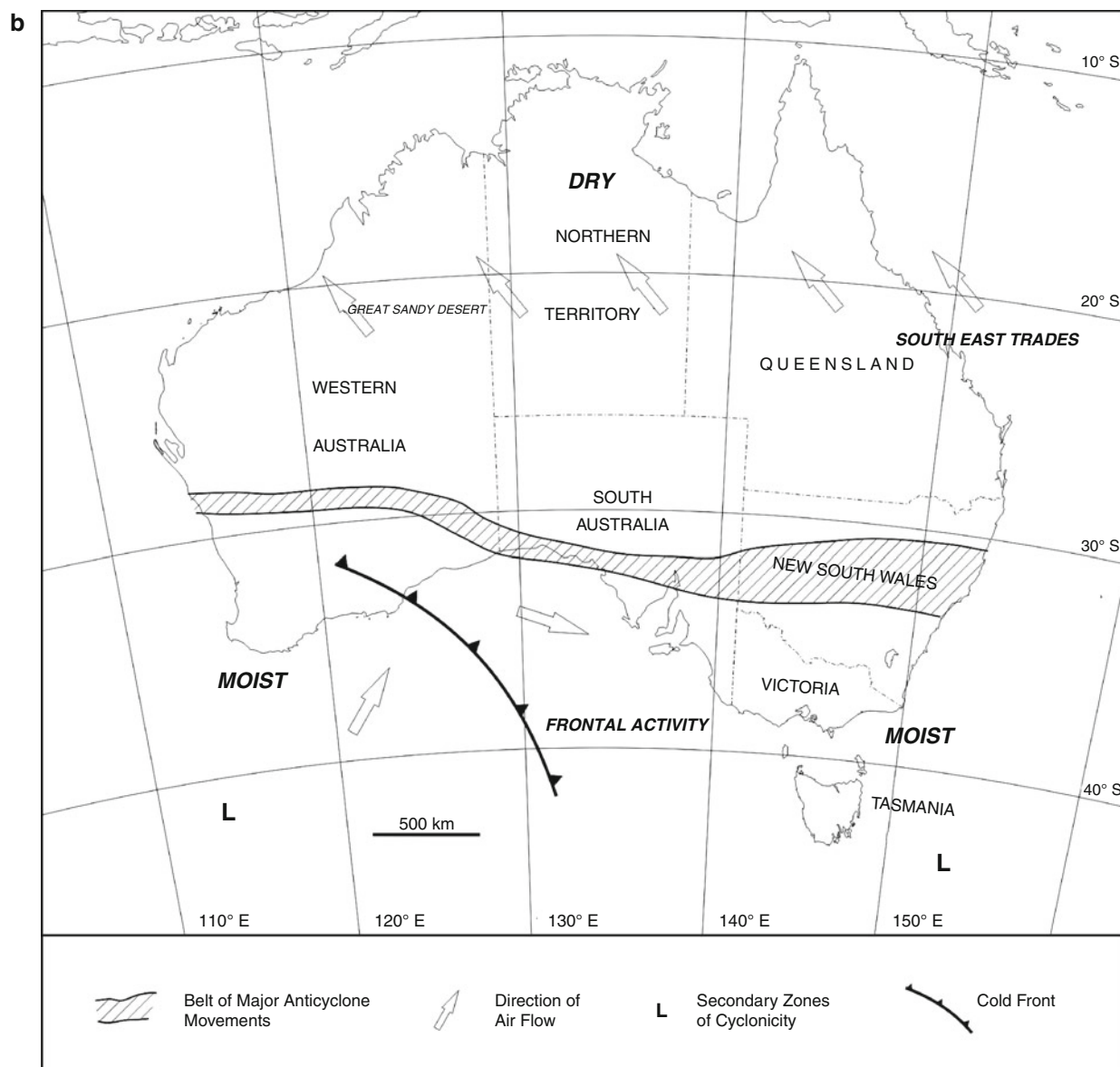


Australia, Climate and Lakes, Figure 2 (Continued)

dry lakes in the interior, and parts of the well-watered southeast and far north are dotted with numerous, mainly small bodies of water. The physical characteristics of many Australian lakes have been reviewed by Timms (1992). The aim here is to highlight just a few examples of various geomorphic types with respect to present and past climatic variations across the country.

The few tectonic lakes can be represented by Lake Eyre and Lake George, both large and ephemeral. Volcanic lakes are common enough in western Victoria; the permanent and deep Lake Keilambete in a crater contains a record of past climatic variations, while the nearby shallow Lake Corangamite in a lava field reflects more

proximate rainfall variations. Lynch's Crater in North Queensland provides a climatic record going back 120,000 years BP. Lakes due to past glacial activity abound in Tasmania, and there are a few on the mainland as well. All are permanent and reflect a different climatic pattern to that typical of Australia, as will be seen from Blue Lake and Lake St. Clair. Lake Selina, in western Tasmania, has yielded a 160,000-year record of paleoclimates, similar to the Lynch's Crater record, but with different vegetation responses due to the two being in contrasting climatic types. Lakes formed by wind action are common both in the inland and along parts of the coastline. They are subject to very different climatic

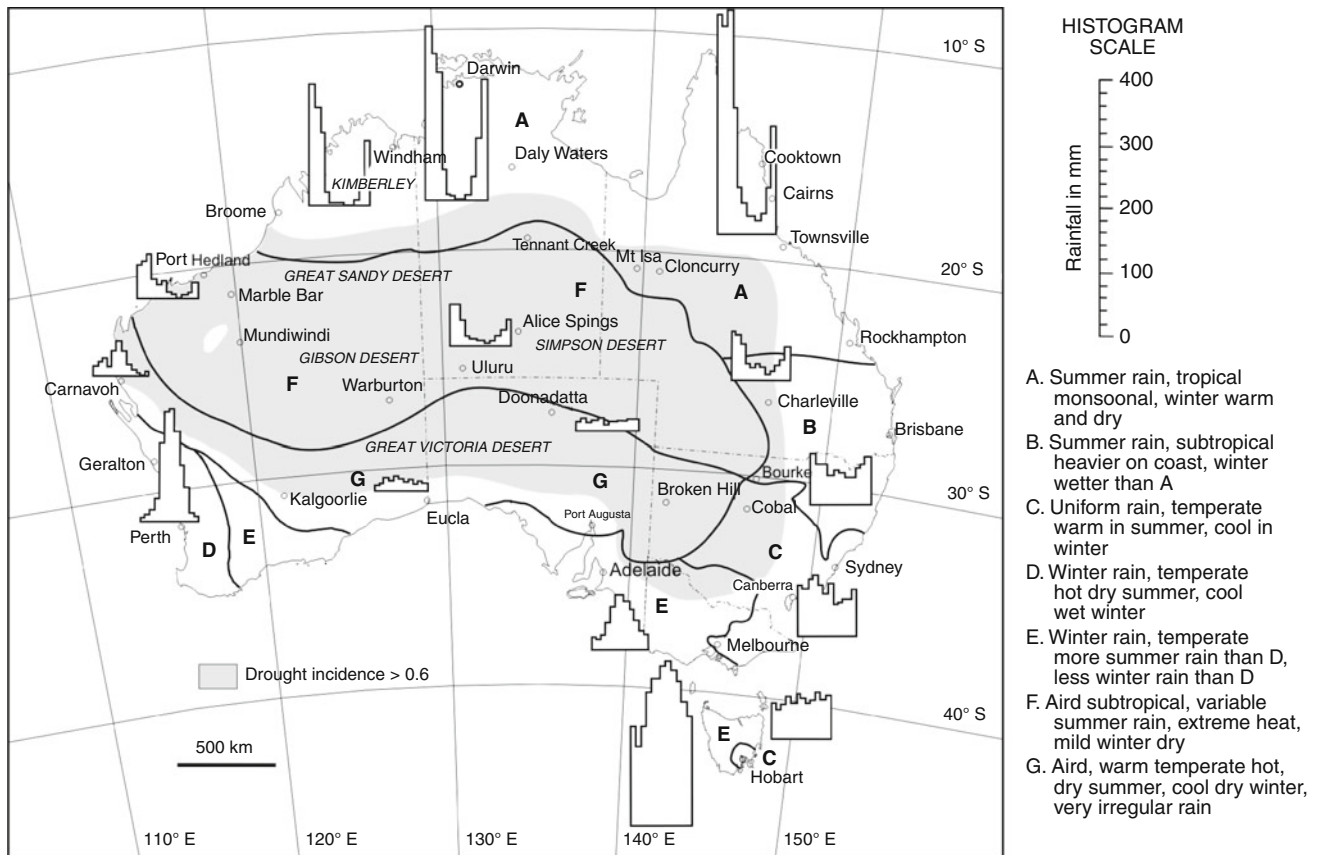


Australia, Climate and Lakes, Figure 2 Simplified synoptic climatology for Australian (a) winter and (b) summer conditions, showing large-scale circulation features (After Bridgman, 1987) (Drawn by Olivier Rey-Lescure, University of Newcastle, NSW, Australia).

regimes as will be seen by examining the inland Salinaland Lakes of Western Australia, Lake Wyara in southwestern Queensland, and the coastal dune Lake Boemijin on southeastern Queensland. Finally, coastal lakes containing marine water abound particularly in southeastern Australia. Studies on the Gippsland Lakes show them to be very different from other types of Australian lakes. They occur also in Southwestern Australia on a rather smaller scale.

Most of these lakes are discussed below (see Figure 1 for locations), but there are separate entries for Lake Eyre, the Gippsland Lakes, and the Salinaland Lakes.

LAKE GEORGE: A tectonic lake located near Canberra in the southeast, Lake George typifies many Australian lakes in that it is shallow and intermittent (Timms, 1992). It lies in a graben against the Cullarin Horst, easily revealing its tectonic origin. When “full,” it is 155 km² in area and 4.6 m deep, but 25,000 years ago, it was much bigger and 37 m deep. A series of raised beaches trace its demise from a permanent lake in a cooler climate with lower evaporation during the last glaciation to its present state (Coventry, 1976). During the last 180 years, its fluctuations in water level have not been dramatic as those in Lake Eyre because it is located



Australia, Climate and Lakes, Figure 3 Summary of rainfall and climatic zones for the Australian continent (After Bridgman, 1987) (Drawn by Olivier Rey-Lescure, University of Newcastle, NSW, Australia).

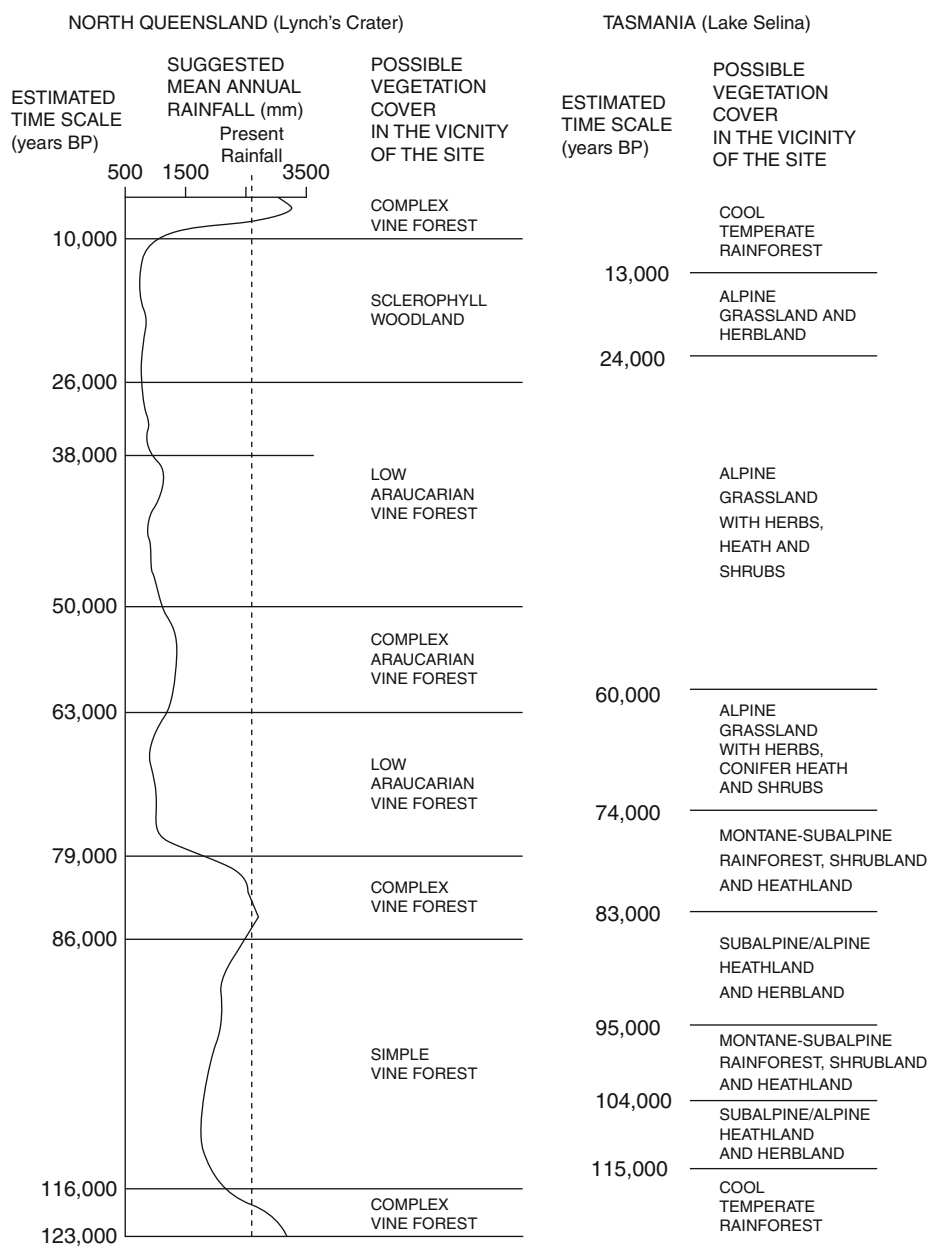
in a more benign climate with lower evaporation and more reliable inputs (Jennings, 1981). Nevertheless, there have been dry periods (e.g., 1940; 2001) and “full periods” (e.g., 1960), but these hardly correspond with ENSO climatic variations as in inland lakes further north.

LAKE KEILAMBETE: A volcanic lake (maar) located on the volcanic plain of western Victoria, Lake Keilambete is 277 ha in area, 11 m deep, and contained in a steep-sided, flat-floored crater (Timms, 1992). Presently, its waters are more than twice as saline as the sea. However, this has not always been the case over its 10,000-year history. Its isolation from regional water tables and “rain gauge” like characteristics bestows a giant evaporimeter status upon it, which is useful in detecting past climatic events in its sediments (Chivas et al., 1986; Jones et al., 1998). For example, the climate was drier, as indicated by higher lake salinities (determined by three independent methods) 2,000–3,000 YBP, and wetter *ca* 4,500–8,000 YBP.

LAKE CORANGAMITE: Located near Lake Keilambete, this lake lies in depressions between lava flows and is much bigger (25,160 ha) but is rather shallow (<5 m) (Timms, 1992). It is the largest permanent saline lake in Australia and was even larger (seven times) during the Holocene. This change was not caused by climatic

variations but due to natural changes in drainage patterns (Currey, 1964). Over the last century, salinity fluctuated widely but has been increasing in recent decades from ~20 to ~60 g/L. Until the 1960s, these fluctuations were largely associated with short-term climatic fluctuations, but the diversion of a major inlet at that time now starves the lake of water. The fauna has changed and the value of the lake for waterfowl, which use it for breeding, feeding, and as a drought refuge, has largely been lost (Williams, 1995). The situation is still reversible.

LYNCH’S CRATER: Now a swamp, Lynch’s Crater is a much older volcanic feature in northeast Queensland. A core tracing its history over 120,000 years (Figure 4) reveals major changes in the surrounding vegetation and hence climate in the eastern wet tropics of Australia (Kershaw, 1978). Tropical complex rainforest dominated during the most recent 10,000 years and again pre-79,000 YBP. In between times, drier vegetation types of Araucarian forest (79,000–26,000 YBP) and sclerophyll woodland (26,000–10,000 YBP) surrounded the crater (see Figure 4). These changes have been associated specifically with rainfall fluctuations, rather than with more general climatic variations, though the correlation between the two, as seen in deep-sea cores, is excellent.



Australia, Climate and Lakes, Figure 4 Vegetation cover and mean annual rainfall for the past 123,000 years from pollen in the sediments of Lynch's Crater, northern Queensland (17°S), indicating major changes in rainfall over time (Adapted from Kershaw, 1978), compared to vegetation cover over a time similar in the sediments of Lake Selina, Tasmania (41.5°S) (Colhoun et al., 1999). Both locations are in eastern Australia. Despite differences in latitude, there are broad similarities in moisture regimes reflected in vegetation changes (Drawn by Olivier Rey-Lescure, University of Newcastle, NSW, Australia).

Changes between wet and dry forests were abrupt, but during the period 38,000–26,000 YBP of the last glacial period, sclerophyllous vegetation slowly dominated, aided in part by more frequent burning by aboriginal people (Kershaw, 1976).

BLUE LAKE, KOSCIUSZKO: The Australian mainland has only four cirque lakes of glacial origin. Blue Lake

is the largest ($A = 14.4$ ha) and deepest ($z_m = 28$ m) (Timms, 1992). It was formed initially in the Early Kosciuszko glaciation *ca* 59,300 years ago and reworked during three subsequent advances *ca* 32,000, 19,100, and 16,800 years ago during the Late Kosciuszko glaciation (Barrows et al., 2001). Blue Lake lies mainly in a rock basin, but thin ground moraine ridges at the lip

add to the depth of the lake. The basin of Blue Lake has *ca* 7 m of bottom deposits due to lacustrine sedimentation, and there are fluvial deltas restricted to nearshore. A submerged ridge of 3 m in the northern corner of the lake may mark a recessional moraine or is possibly a protalus rampart being built at the toe of a winter snow patch. The lake is permanent, has a stable water level, and contains extremely pure water of very low nutrient status, like few others in Australia. Also, it is one of only a few lakes in Australia to freeze over in winter and hence have a dimictic thermal regime (stratified in winter and summer), as opposed to most other lakes which are monomictic (stratify only in summer) (Raine, 1982).

LAKE ST. CLAIR: A piedmont glacial lake in the highlands of Tasmania, Lake St. Clair is the deepest natural lake in Australia at 165 m (Derbyshire, 1971). It is also comparatively large (2,818 ha). The location of the glacial trough is due to bedrock geometry and preglacial topography, but the detail is due to many glaciations. The Last Glaciation retreated in stages and concluded locally about 9,000 years ago (Kiernan, 1992). The lake occupies four rock basins, beyond the meeting of four valley glaciers. The deepest of these lies downstream of the entry point of two lateral glaciers that spilt over from the Central Plateau. There is also a fifth, much shallower basin in end moraine due partly to excavation by another lateral glacier. This impounding end moraine is less than 50 m deep, so excavation due to glacial action is great by Australian standards. Like other glacial lakes in the temperate, moist climate of Tasmania, Lake St. Clair is permanent and has good quality clear waters, with little variation in water levels.

LAKE SELINA: A small lake in a Pleistocene-glaciated valley in western Tasmania, Lake Selina escaped the most recent Wisconsin glaciation. A 397-cm core from its sediments reveals a climatic history for the area dating back 160,000 years (Colhoun et al., 1999) shown in Figure 4. For the last 14,000 years, the area has been clothed in cool temperate rainforest dominated by *Nothofagus cunninghamii* (Southern Beech). During the Wisconsin glaciation, the surrounding vegetation was of alpine grassland and heathland grading to shrubs at *ca* 60,000 YBP. Going back another 55,000 years, the surrounding vegetation oscillated between montane rainforest and shrub land and alpine/subalpine heathland and herbland. Beyond 115,000 YBP, the pollen deposits tell of cool temperate rainforest like that of the present. These vegetation changes point to climatic fluctuations between the present cool, wet temperate conditions to periods when average temperatures were $> 3.5^{\circ}\text{C}$ (and up to 6.5°C in mountains nearby) cooler and even a time when temperatures may have been warmer.

LAKE WYARA: This saline lake lies in southwest Queensland adjacent to the Paroo River into which it occasionally overflows (Timms, 1998). Generally, it fills and dries episodically and is very much influenced by rainfall patterns associated with atmospheric circulation patterns in the Southern Hemisphere as measured by the Southern

Oscillation Index (Karoly et al., 1998). During strongly negative SOIs, there is below average rainfall in northern and central Australia and Lake Wyara dries (El Niño years), while conversely during strongly positive SOIs, rainfall exceeds the average and Lake Wyara fills, sometimes to overflowing its generally closed catchment (La Niña years). At such times, it is 3,400 ha in area, nearly 7 m deep, and almost fresh. More normally, it is 2,500–3,000 ha in area, 1–2 m deep, and hyposaline-mesosaline. Its large catchment and size make it the best barometer of rainfall variation among the lakes of the Paroo region. The correlation between the SOI and full and dry periods over the last 110 years is highly significant ($r = 0.622$, $n = 34$) (Timms, 1998).

Lake Wyara lies at the edge of the Paroo floodplain and on a tertiary fault. The relative contribution to the depth of its basin by faulting reduced deposition at the edge of the floodplain, and deflation is unknown. Deflation is probably the most important, but the eastern shore lacks Holocene lunette dunes that are present downwind of many other local lakes which tend to fill and dry seasonally. However, a subdued much older lunette dune is present, indicating its greater age and response to different climatic conditions in the past.

LAKE BOEMINJIN: The east coast is fringed in many places with siliceous dunes which are particularly expansive in southeast Queensland. Some offshore islands are entirely of such sands, including the world's largest sand island, Fraser Island, 200 km north of Brisbane. Given the ready porosity of these sands, it is surprising Fraser Island is dotted with lakes well above sea level. These lakes, of which Lake Boemjin (or Boemingen) is a large example, are perched above the widespread water table and owe their origin to special processes (Bayly, 1964).

Lake Boemjin ($A = 297$ ha, depth < 5 m) lies in a deflation basin 74 m above sea level. The surrounding dunes are well vegetated, and the climate is subtropical with no dry season. Fine organic material from the leaf litter is washed into the hollow, percolates downwards, and, by podzolization, forms a B-horizon of relatively impermeable cemented sand. A perched water table results. Other lakes in the area are of similar origin, but instead of lying in a simple deflation hollow, the hollow is more complex (e.g., Lake Bowarrady) or lies within a parabolic dune (Lake Poona) or is due more to damming than deflation (e.g., Brown Lake on Stradbroke Is) (Timms, 1992).

Whatever their geomorphic origin, these lake waters are humic due to a large dissolved organic matter fraction. This imparts unique properties to the lake associated mainly with its low pH (*ca* 4–5), abundance of bacteria consuming the dissolved organic matter, and a simplified food chain based on unusual food energy source. Variants of perching and geomorphic origin result in slightly different limnological conditions in coastal dune lakes along the east coast (Timms, 1992), but all owe their presence to some degree to climatic conditions suitable for podzolization of siliceous sands.

Australian lakes are different in many respects to those on other continents or large islands due largely to the great age of landscapes and the limited extent of Pleistocene glaciations. Most lakes are intermittent and many are saline. Lakes due to glacial action are relatively uncommon, except in Tasmania, while wind action is important in the inland and in coastal areas. Also, mainly in coastal southeastern and smaller ones in southwestern Australia, many lakes are due to Holocene marine oscillations. The contrasting climates in northern and southern Australia impose differing hydrological conditions and vegetation in the catchments, but, as [Figure 4](#) shows, there are broad similarities in the rainfall regime over geological time. The sediment record tells a very complex story of fluctuating climates, varying rainfall patterns, and change in lake levels during the Pleistocene.

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Cross-references

[Australia, Coastal Paleolakes of "Swanland"](#)
[Climate Change Effects on Lakes](#)
[World Lake Database: International Lake Environment Committee Foundation \(ILEC\)](#)

AUSTRALIA, COASTAL PALEOLAKES OF "SWANLAND"

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Definition

Very strong seasonality is a feature of Southwestern Australia, as well as parts of South Australia and some other areas of the continent. This means that many large rivers tend to be greatly reduced in discharge during dry seasons when rainfall in their interior basins may be as little as zero. The southwestern and southern coasts are subject to almost continued swells set up by storms in the Southern Ocean. As a result, regardless of local meteorological systems, there is almost constant heavy wave action from the southwest. On the west coast, the beach sands migrate from south to north, and on the south coast, they migrate from west to east. In this way, even major estuaries are seasonally blocked and become lakes.

In addition, during dry seasons, with onshore winds aided by the diurnal sea breeze, major dune accumulations are observed. Furthermore, during the Holocene, major climate cycles introduce wetter and dryer intervals at 1,500–3,000-year periodicities. The geochemistry of the sands is also a significant factor. In the south, the beach sands are prominently derived from granite-gneiss weathering, but on the west coast, north of about 35°N, the sands are markedly calcareous due to a mix of debris from large foraminifera, corals, and crushed bivalves. When blown up into dunes, these sands are loose, but after a few wet cycles, they begin to dissolve and CaCO₃

cement begins to lithify the dunes to a rock known as eolianite. After a few millennia, this rock is still quite friable, but after 10, 000 years or so, it becomes a resistant limestone (widely favored for foundation stones by home builders). In South Australia (S.E. of the Murray entrance), the entire Quaternary, thanks to a slight crustal uplift, is represented by about 18 interglacial intervals of eolianite building (Sprigg, 1979). The Murray River is Australia's largest drainage system, yet from time to time it has been blocked by littoral drift and large coastal lakes created, notably Lake Alexandrina. Early colonists' dreams of using the Murray for a regional port were dashed by this seasonality.

In Western Australia, the Quaternary eolianites reach elevations of more than 300 m in the region of Shark Bay and are a major feature of the coastline for over 1,000 km. In the coastal plain of the southwest, their highest elevations are less than 100 m, forming irregular hills up to 10 km inland. During the low sea-level phases of the Pleistocene, the main river valleys were cut down by the increased discharge (heavy precipitation in the coastal ranges) and channels cut through the eolianite ridges. With the interglacial rise of sea level, large paleolakes were created. After reaching their maxima, outlet channels were formed, and all the major examples are now, at least partly, tidal estuaries. They are characterized by large inland water bodies connected to the ocean by narrow channels. Examples include:

- (a) Melville Water and Perth Water, fed by the Swan and Canning rivers with their combined exit channel at Fremantle. Highly fossiliferous spits (with marine fossils) mark the trace of the last interglacial marine inundation, when sea level reached at least 5 m above present (see map in Jutson, 1934, from Somerville (1919); for "elevation," read "emergence," i.e., a eustatic factor). Today, the salinity is only slightly brackish at times. An appreciation of the coastal limestone may be found in an admirable ecological and historical volume on the Perth area by George Seddon (1970). The eustatic nature of the emerged ridges was first recognized by Fairbridge (1954), but the wind-blown nature of the eolianites ("Coastal Limestone") was recognized by the earliest voyagers and their karstic features correctly explained by Charles Darwin (1845).
- (b) Peel Inlet, with its narrow outlet at Mandurah and fed from the plateau by Murray Williams and the Serpentine. There is some tidal exchange, so the waters are rather brackish.

Along the coast, south of Peel inlet, are three elongate water bodies of totally distinct origin. They are entirely of Holocene climatic-eustatic causes, being an echelon (Lakes Preston and Clifton) and separated by major beach ridges built up by episodes of strong southwesterly storms. These two, Preston and Clifton (respectively 28 and 20 km long but only 1 km across), are completely isolated from the ocean, but a third one, the Leschenault Inlet, is open at its south end near Bunbury which is influenced by intake from the Collie River. All are strongly influenced by the carbonate sands that dominate the beaches and in places are marked by distinctive shell beds.

On the south coast, the impact of the Antarctic swells tends to build beaches toward the east, and the eolianite topography controls much of the coastline. Seasonal closures of the lower, estuarine courses of the major rivers create ephemeral lakes. Deep River (which heads in a small lake 70 km inland) and the Frankland River both debouch into a wide embayment determined by eolianite hills resting on Precambrian prominences. The same setting determines the remarkable form of King George Sound (with the port of Albany), which provided HMS Beagle a safe haven and Charles Darwin an opportunity to study the eolianite. Much later, Fairbridge and Teichert (1953) were able to recognize multiple generations in it, separated by paleosols (with evidence of cool, wet cycles) and even multiple oscillations of sea level (with marine brands, some from the last interglacial); innumerable small paleolakes conditions are evidenced by localized piping and karst phenomena.

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[Australia, Climate and Lakes](#)

B

BAIKAL, LAKE

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Introduction

Lake Baikal contains one fifth of the freshwater resources of the world, i.e., according to the recent unpublished studies of Alekseev et al. (2002), 23,615 km³. This Russian lake, the deepest in the world (1,637 m), is located in southeastern Siberia. It is 636 km long, from 51° 27'N to 55° 46'N, and covers an area of 31,722 km². Lake Baikal, which appeared 25 million years ago, is the oldest lake on Earth. Owing to its large size and great age, speciation was responsible for a very rich endemism which is very vulnerable to pollution.

One of the most famous lakes in the history of limnology

Russians conquered the region of Lake Baikal in the seventeenth century. Some learned travellers, such as ambassador Spafari, and exiles, such as the protopope Avvakum, described the lake. In the eighteenth century, soldiers and sailors, such as Bering, needed a map, since a navy was created on Lake Baikal. During the naturalist expedition of Pallas and Georgi in 1775, Pushkarev surveyed the topography of the lake and its surroundings for the first time. Lake Baikal entered the scientific world in the 1860s, when numerous Polish revolutionaries were deported to the region of Irkutsk. Some of them were scientists and studied the lake. Dybowsky, a specialist in gammarids, was the first Baikalian biologist and Chersky was the first geologist. The construction of the Trans-Siberian Railway, which reached Irkutsk in 1898, favoured human migrations and increased the need for scientific

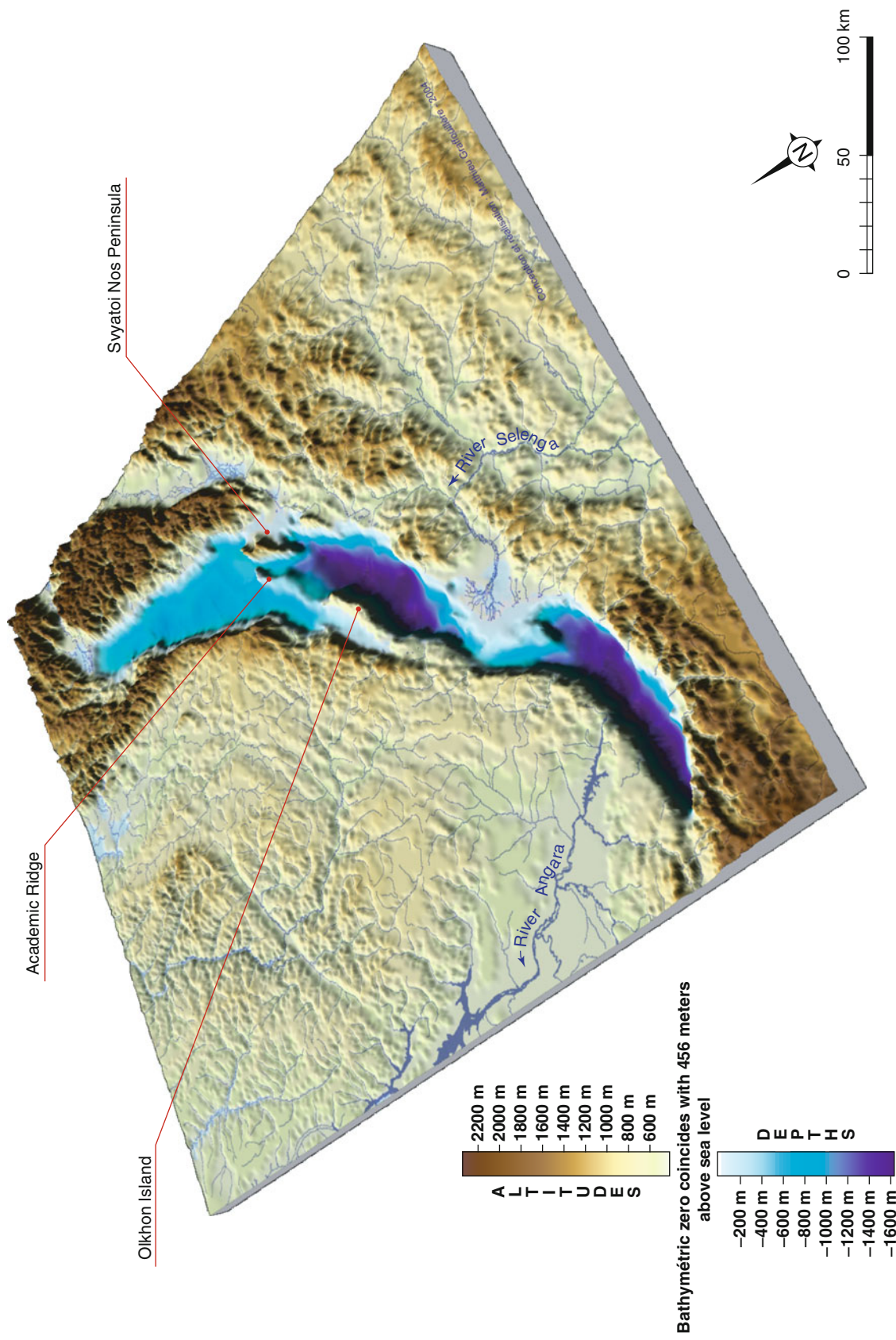
studies for the safety of the ferries crossing the lake. The Trans-Siberian Railway had its own scientific journal, in which Obruchev, named “the father of Siberian geology,” wrote many articles about the faults of the region and the origin of Lake Baikal. After many expeditions from 1896 to 1902 and 274,369 soundings, Drizhenko produced the first bathymetric map of the lake.

In 1916, the Russian Academy of Sciences created the Commission for the Study of Lake Baikal, and, after the Revolution, in 1918, the new government founded the Biological Station of Bolshie Koty on the shore of the lake, and later, in 1928, the Limnological Station of Lake Baikal in Listvyanka. Vereshchagin, one of the world's most famous limnologists (Martinson, 1995), managed this station until 1942. Some well-known biologists of the postwar period, such as Kozhov, began their studies under the direction of Vereshchagin. After the war, the Baikalian Limnological Institute became one of the biggest in the world. Equipment was plentiful, for example laboratory ships. The Institute of Oceanology in Moscow regularly provided its submarine for the study of Lake Baikal. Since the collapse of the Soviet Union, there have been financial difficulties, but new collaborations have also emerged, particularly with American and Japanese researchers.

A very old rift lake

The Baikal tectonic valley is the central part of a complex rift zone located in Central Asia from the Mongolian Busingol and Khubsugul basins to the Tokko basin. The Baikal Rift Zone extends over 2,000 km above an anomalous mantle uplift. Compared with other rifts, particularly the East African Rift, the Baikal Rift Zone is the farthest from any ocean and from a major plate boundary. According to Molnar and Tapponier (1975) and Tapponier et al. (1982), the collision of the Indian Plate with and its penetration into the Eurasian Plate caused extrusion

M. Graffouillère, 2004, after Soviet topographic and bathymetric maps 1/200000 (courtesy L. Touchart) and GLOBE-NGDC



Baikal, Lake, Figure 1 Hypsometric and bathymetric digital elevation model (DEM) of Lake Baikal and its surroundings (Graffouillère, unpublished, after Soviet topographic and bathymetric maps 1:200,000 and GLOBE-NGDC).

tectonics, beginning in Indochina, then extending north like strike-slip faults in China and like a rift in the Baikal region. This passive theory is well accepted today by most geologists (Mats, 1993). Nevertheless, Zorin (1981) and Logatchev (1984) preferred the active theory, according to which the Baikal Rift Zone is an independent phenomenon induced by a local asthenospheric upwelling. In contrast with the East African Rift, volcanism is of secondary importance in the expansion of the Baikal Rift.

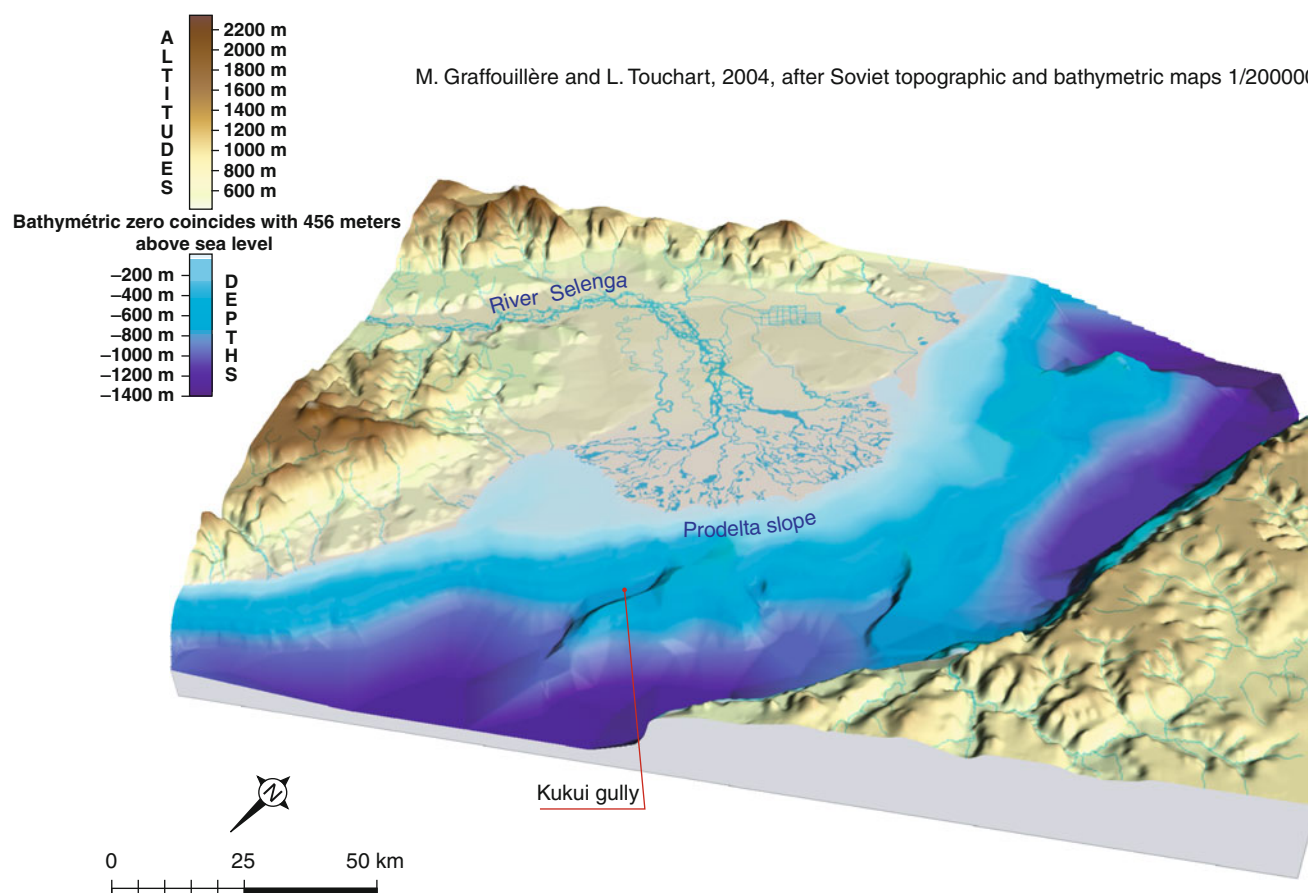
The lake itself lies in two deep tectonic basins separated by a submerged (Academic Ridge) and emerged (Olkhon Island, Svyatoi Nos Peninsula) uplift (Fig. 1). The southern basin from which rifting propagated is deeper and older than the northern basin. Oligocene sediments of the southern basin form the base of 7,000-m-thick deposits. The coastal landscape of Lake Baikal consists of rift shoulders and fault scarps. The most common aspect is a system of steep triangular facets with some intermediate steps (Ufimtsev, 1991). The basal slopes of the tectonic scarps form plunging cliffs.

The southern tectonic basin is made of two topographic depressions (Fairbridge, 1968), since the prodelta slope of the Selenga River cuts the basin in two parts (Fig. 2). Little

sediment is deposited from the central delta front, but fluvial material is rather channelled through a fault-controlled sublacustrine canyon named Kukui Gully towards the northeast (Karabanov and Fialkov, 1987). On the shoreline, fluvial deposits are redistributed and accumulate along bay head beaches, bay bars and spits.

Water temperature and mixing of the world's deepest lake

Lake Baikal is dimictic. After the homothermy of November, there appears a light slush (*shuga*), a mixture of internal ice consisting of anchor ice and melting snow, which turns into a dense and opaque sludge (*salo*) by the end of the month. By December, the drifting of the pancake ice (*blinchaty led*) causes the collision of the ice plates and rafts. The lake freezes over by the second half of December (this often happened at the beginning of the twentieth century, but seldom happens now) or, frequently for the last 20 years, by the first half of January. By February and March, the ice cover (*l'dina*) is 70 cm thick in the southern part to 130 cm thick in the northern basin, above a thermal inverse stratification of the water masses. By mid-April, the ice begins to thaw and break apart. By



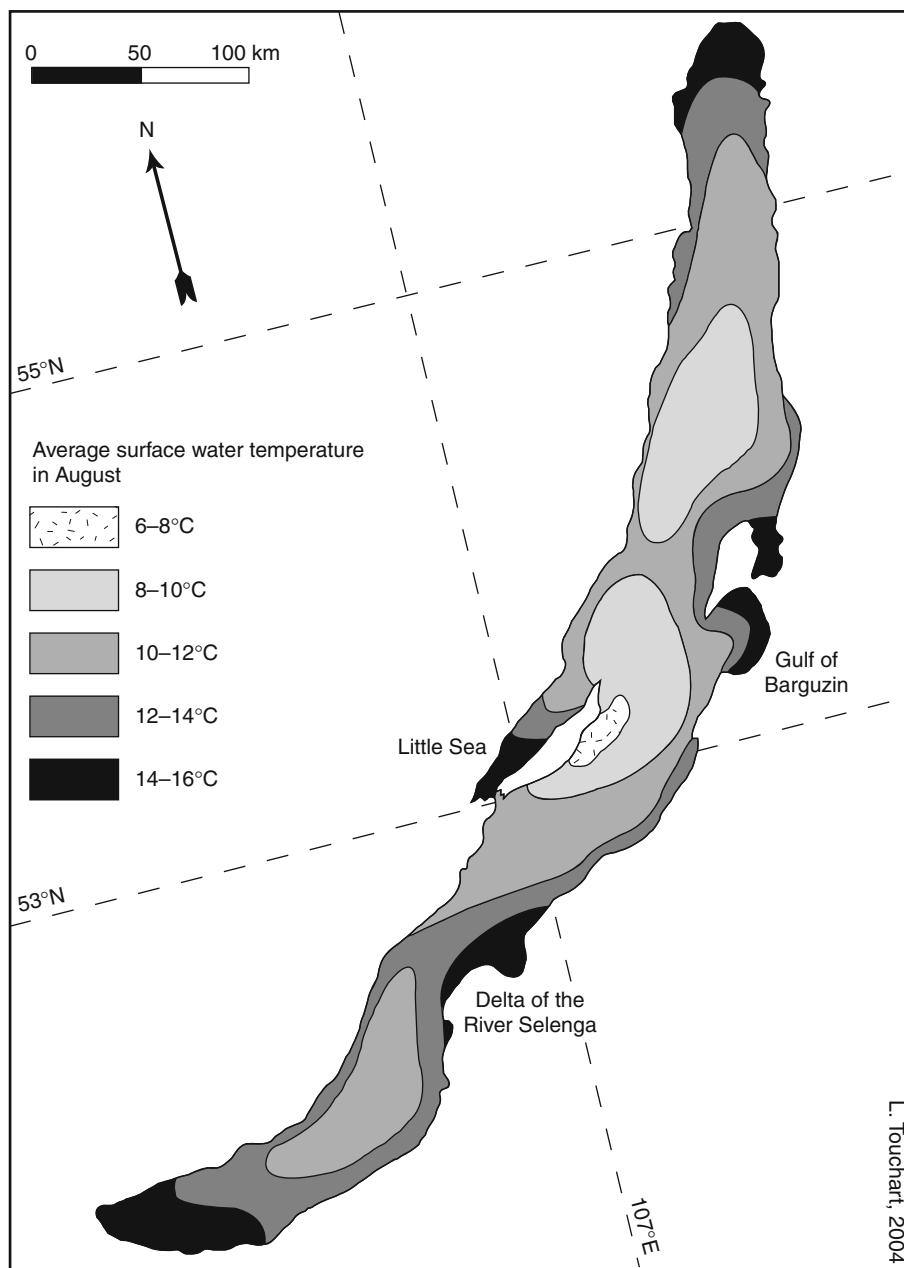
Baikal, Lake, Figure 2 Hypsometric and bathymetric DEM of the delta of the Selenga River (Graffouillère, unpublished, after Soviet topographic and bathymetric maps 1:200,000).

May, the ice cover disappears from the southern basin and the second period of homothermy occurs. By June, only some floes float in the northern basin. The warm Siberian summer causes a direct stratification and, at the August maximum, the offshore surface layer reaches a temperature of 10°C (Fig. 3) above a 50- to 90-m-thick epilimnion. In the bays, the surface temperature sometimes exceeds 16°C .

This enormous water volume, slowly storing and redistributing energy, influences the climate of the land

around it and creates a limnoclimate which propagates along the Angara fluvial outlet. For example, in Irkutsk, 65 km from Lake Baikal, the annual thermal range is about 37°C , whereas the difference between August and February is about 45°C in the meteorological stations of south-eastern Siberia that are uninfluenced by the lake.

Dimixis of Lake Baikal is in fact largely complicated by its huge depth. During homothermy, free convection only occurs down to 250 or 300 m (Shimaraev et al., 1993). Only this surface layer is regularly mixed and passes in



Baikal, Lake, Figure 3 Map of the surface water temperature of Lake Baikal in August (After Akademiya Nauk SSSR, 1962; Touchart, 1994, 1998, 2003).

autumn and spring through the temperature at which surface water has its maximum density, i.e., 4°C. Below, water renewal is episodic. But since the temperature at water has its maximum density decreases with increasing depth, the base of the mixed layer may locally move to a depth at which its temperature reaches the temperature at which water has its maximum density (Killworth et al., 1996). The sinking plumes which result from the phenomenon of thermobaric instability allow the deep ventilation of Lake Baikal, so the concentration of dissolved oxygen reaches 9 mg l⁻¹ at the deepest points of the central basin.

Permanent wind-drift currents and autumnal waves

Numerous local currents certainly disturb the general circulation, but Lake Baikal is above all affected by long-lasting or permanent wind-drift currents (Fig. 4). During ice-free seasons, the 50-m surface layer has a cyclonic movement with maximum velocity in spring. It consists of two major cyclonic cells in the northern basin, one in the central depression and two in the southern basin with seasonal oscillation (Galazy, 1993). A minor cyclonic cell affects the Gulf of Barguzin and an anticyclonic one affects the Gulf of Larch Trees, which gives birth to the Angara outlet. The strait of Little Sea gives a linear direction to its current. During ice-cover seasons, the currents are minimum, but the same directions are preserved, except in the Gulf of Larch Trees.

Two dominant and regular winds are channelled through the rift valley. The Kultuk ("dead-end wind"), a very common southwest wind, blows especially in autumn. During anticyclonic conditions, the Verkhovik ("upper wind") is a frequent north or northeast wind which is stronger in the daytime. The very long fetch of these two winds causes dangerous waves which may reach a height of 6 m in the northern basin (Fig. 5). Transverse winds are less common and blow only locally over a shorter distance, but some of them are stronger. Very sudden autumnal waves are due to the Sarma, a transverse northwest stormy wind first channelled by the Sarma valley then by the strait of Olkhon Portal. In spring, the Barguzin, a transverse northeast wind, assaults the lake in powerful and impetuous gusts, breaking the ice of the central basin.

Chemistry, water quality and anthropogenic pollution

Because of the crystalline lithologic character of the drainage basin, the waters of Lake Baikal are poorly mineralized. The average natural amount of dissolved matter in the lake is 0.096 g l⁻¹ (Vereshchagin, 1949; Votintsev, 1961). Major ions (63.5 mg l⁻¹ HCO₃⁻, 15.2 mg l⁻¹ Ca²⁺, 5.2 mg l⁻¹ SO₄²⁻, 3.8 mg l⁻¹ Na⁺, 3.1 mg l⁻¹ Mg²⁺, 2.0 mg l⁻¹ K⁺) are uniformly distributed at all depths of the three basins throughout the year. The average concentration of silica increases with depth from 1.1 to 5.5 mg l⁻¹ and seasonally varies with the consumption of the diatoms in the upper layer.

Lake Baikal is oligotrophic. Nutrients are unequally distributed at different depths and in the three basins, with a maximum in the southern part of the lake. Also, their distribution varies throughout the year, with an annual maximum by February and a secondary maximum by June. The annual minimum occurs in August, coinciding with the maximum organic consumption and water temperature.

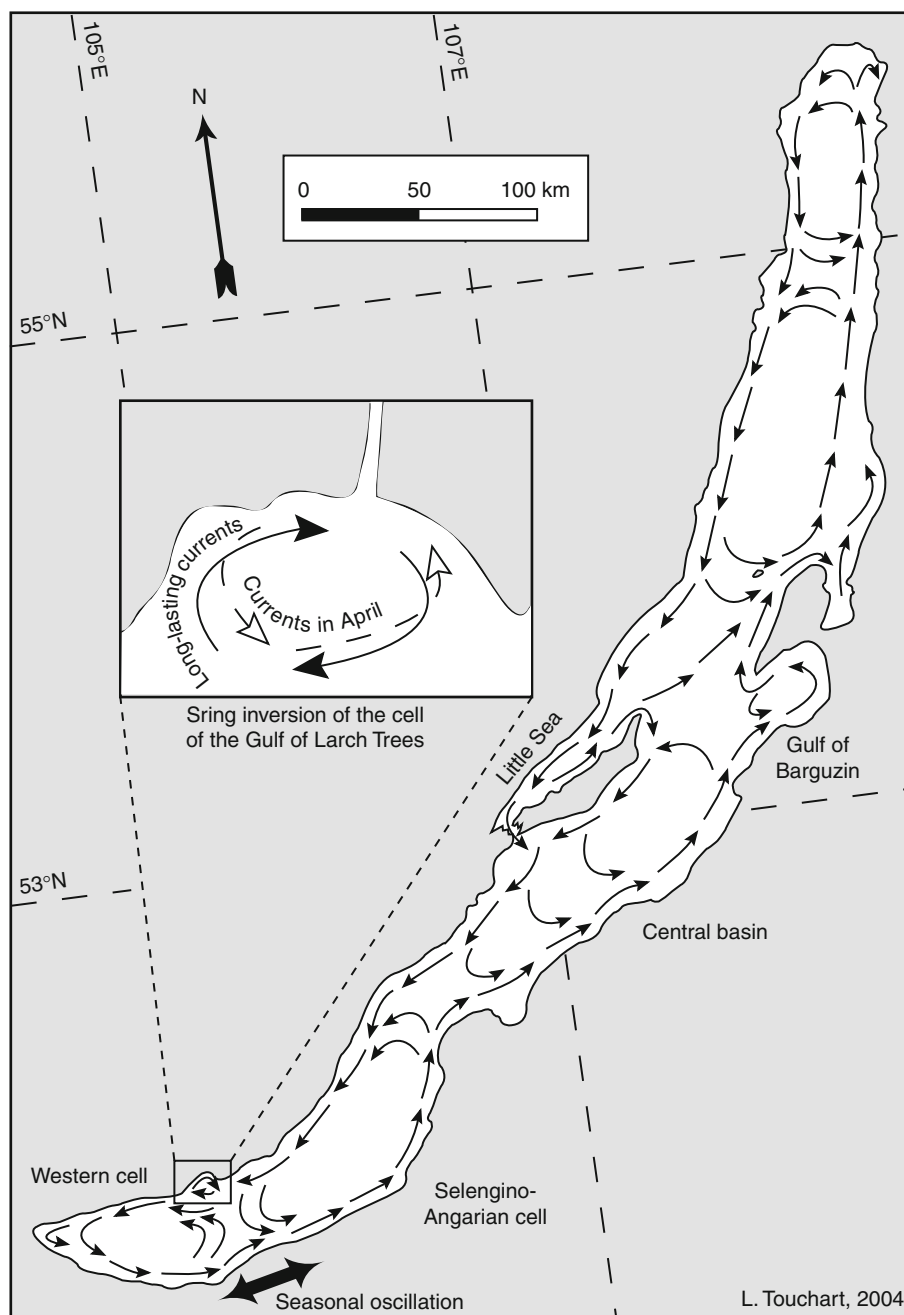
Significant anthropogenic pressure on Lake Baikal began in the 1950s with the construction of the Irkutsk hydroelectric power plant 60 km downstream of the Angara outlet. The resulting 80-cm rise of the average lake water level disturbed some littoral regions, increasing coastal erosion. The ensuing water turbidity destroyed some spawning areas. The most important development in the Baikal region was the construction of the Baikalsk Pulp and Paper Plant on the shore of the southern basin. This location took advantage of the large volume of pure water, the abundance of taiga raw material and the facilities for exporting the production via the Trans-Siberian Railway. This mill came into operation in 1966. Despite the construction of an efficient wastewater purification plant in 1969, which was modernized in the 1970s and recently transformed into a semi-closed circuit, the plant pollutes the lake. Incompletely treated discharges of wastewater contain PCBs and phenols. Lake sediments are contaminated over 3–14 km² around Baikalsk (Sukhodolov, 1996), and significant pollution affects the upper water layer as far as 15 km east of the paper mill (Fedorov et al., 1992).

Today, only 80,000 residents live along the 2,000-km shoreline of Lake Baikal, and the density in the drainage basin is less than five inhabitants per square kilometer. Anthropogenic pressure is concentrated in the southern basin, around the Baikalsk Pulp and Paper Plant and the mouth of the Selenga River, which brings pollutants from the Buryat towns, especially from Ulan-Ude.

Biogeographic characteristics of Lake Baikal: a very high degree of endemism

The very long isolation of Lake Baikal in connection with its large size has allowed the development of 1,085 plant species (including 679 diatoms) and 2,491 animal species, among which 80% of the pelagic organisms are endemic, comprising 87 unique genera and 11 exclusive families (Mazenova, 1995). These endemics have two origins. Some of them colonized the lake during successive periods when Baikal communicated with other regions, particularly with the Arctic Ocean. The second origin, the most frequent one, is due to evolution on the site itself (Kozhov, 1963; Kozhova and Izmet'eva, 1998).

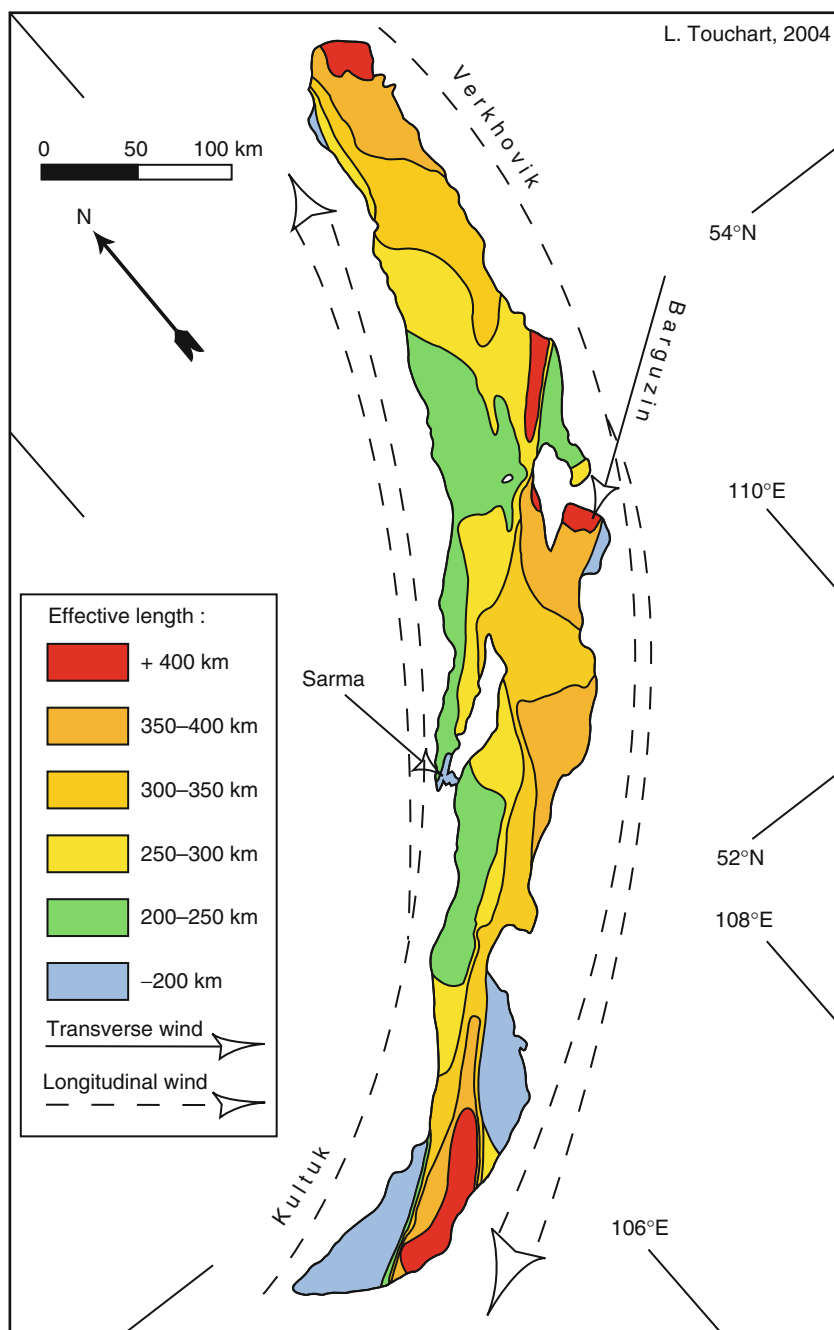
The Baikal seal (*Phoca sibirica*), named *nerpa* by the Siberians, is supposed to have arrived by a very ancient migration, using the Yenisey and Angara river systems, and then to have evolved within the lake. Parasitological analogies with the arctic seal (*Phoca hispida*) confirmed that this freshwater mammalian is descended from a marine form. But genetic studies showed that its



Baikal, Lake, Figure 4 Map of the long-lasting wind-drift currents in the upper layer of Lake Baikal (After Sokolnikov, 1964; Mankovsky, 1964; Verbolov, 1993; Touchart, 1994, 1998, 2002).

colonization is very ancient, probably in the Miocene–Pliocene (Pastukhov, 1993). Owing to natural selection, the Baikal seal is distinct from its ancestors, with higher haemoglobin concentration in its blood, stronger claws and additional teeth, presumably because its dives are deeper, freshwater ice is harder and the fishes consumed are smaller than those in the Kara Sea.

The major source of food of the Baikal seal, the fat fish (*Comephorus baicalensis* and *Comephorus dybowskii*) of the lake, is a good example of indigenous endemic genera (Fig. 6). Named *golomianka* (“naked fish” because it is scaleless) by the Siberians, the fat fish is a half-transparent animal living in the deepwater masses. It is the only viviparous fish in which all females and numerous males die



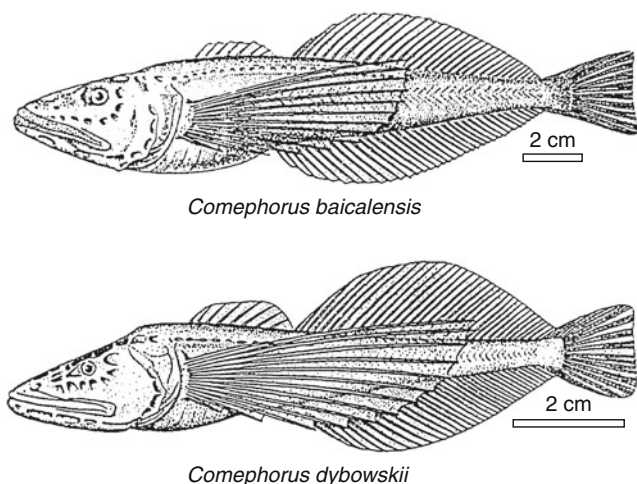
Baikal, Lake, Figure 5 Map of the wave potential of Lake Baikal (Touchart, unpublished).

just after the birth of the larvae. It was probably a blind alley in natural evolution and speciation (Sideleva, 1982).

Protected natural areas

Lake Baikal and its surroundings have been protected since the decree passed in May 1960 on defence of the coastal forest and fishing supervision (Touchart, 1998).

The resolution of the Soviet Cabinet passed in June 1971 prohibited timber-floating on the tributaries and required the construction of wastewater purification plants in the drainage basin. In 1974, the Russian Nature Conservation Society created the “Commission for the Study and Public Awareness of the Questions about Nature Conservation of Lake Baikal,” which established special protected areas,



Baikal, Lake, Figure 6 The fat fish of Lake Baikal (After Sideleva, 1995).

especially so-called nature monuments. A resolution of the Communist Party Central Committee, passed in April 1987, created the protected zoning of the whole drainage basin (Vorob'yev and Martynov, 1989).

There are four statuses for special protected areas around Lake Baikal: 267 nature monuments (*pamiatniki prirody*), 26 preserved territories (*zakazniki*), two national parks (*natsionalnye parki*) and three nature reserve areas (*zapovedniki*). The most rigorous status is that of nature reserve, in which all activities except scientific research are prohibited (Gusev, 1986). The Barguzin Reserve (2,632 km²) was created in 1916, the Baikal Reserve (1,657 km²) in 1969 and the Baikal-Lena Reserve (5,600 km²) in 1989.

A certain continuity prevailed after the collapse of the Soviet Union. The federal law "On the protection of Lake Baikal," passed in May 1999 and often called "Baikal law" by the Siberians, has resulted in numerous government orders being issued, among which are the decree of September 2000 confirming the ecological zoning of the protected areas around Lake Baikal and the decree of January 2002 strengthening the protection of the Baikal seal and the Baikal salmon (*omul*).

Conclusion

Lake Baikal is a unique lake, with a rich biological endemism because of its age. Except in the southern basin, the water quality remains excellent for two reasons: protection is rigorous and the enormous volume of water, with a great diluting ability and a very long water renewal, allows it to be preserved in spite of the anthropogenic outflows. However, the threats are great and it is urgent to finish the construction of the completely closed water circuit of the paper mill or to cease the production of cellulose by a reconversion of the Baikalsk Pulp and Paper Plant. Since 1996, Lake Baikal has been on the UNESCO World Natural Heritage Site List.

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BALATON LAKE IN HUNGARY

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Introduction

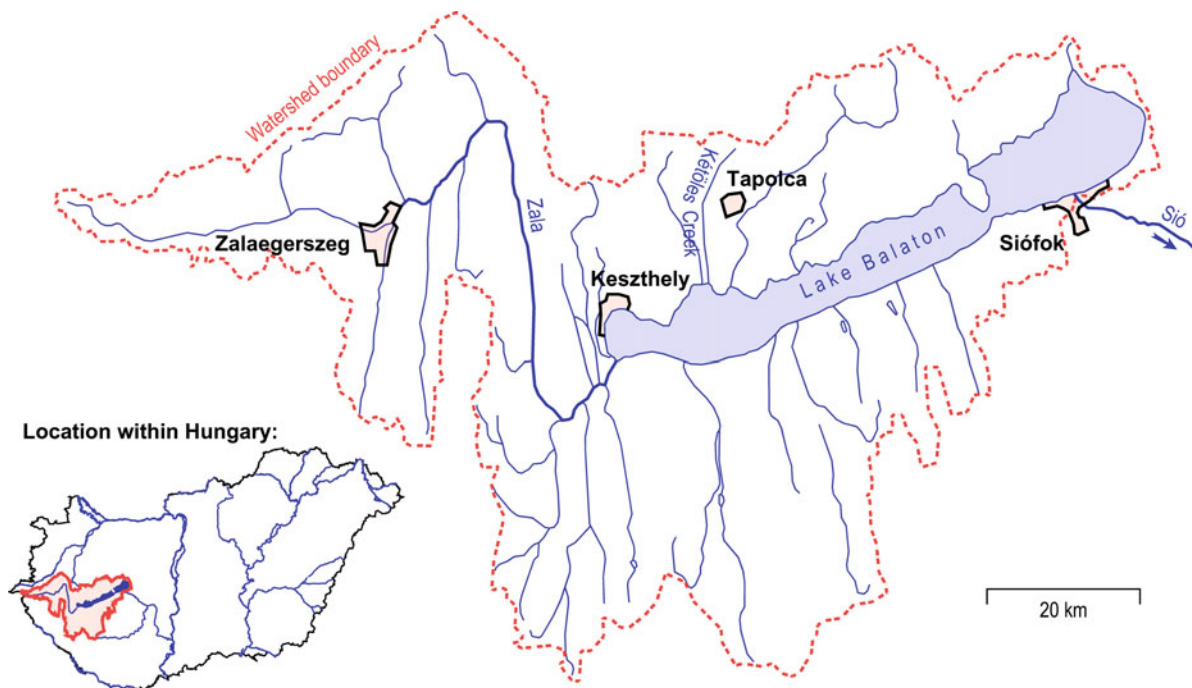
Lake Balaton is situated in the western part of Hungary. It is the largest lake in Central Europe with a 595 km² surface area. Its length is 78 km, the average width is

7.7 km and the average depth is 3.3 m. The maximum depth reaches to about 12 m in the *Strait of Tihany* separating the western and eastern bays of the lake. The total length of the shoreline is 235 km. The extent of the catchment area is 5,775 km².

The beginning and process of geologic development of Lake Balaton is a long-disputed problem. The different researchers are dealing with the history of the present lake bed itself, the catchment area or its wider surroundings. Accordingly, the estimations are varying from 12,000 years to 18,000–20,000 years.

Hydrographic description

The main tributary is the *Zala River*, flowing into the *Keszthely Bay* on the western part of the lake. Its drainage area occupies 45% of the total catchment area. The north-oriented [Figure 1](#) shows the creeks and artificial canals feeding the lake. The boundaries of their sub-catchments roughly indicate the extent of the former marshy areas intermittently inundated by the lake in the past before the regulation of the water level (1863). After two trials with different structures, the present concrete and steel weir at Siófok was inaugurated in 1947 through which the excess waters can be drained by the navigable *Sió canal* into the *River Danube*. The permitted range of water level variation was introduced in 1977, with a maximum of 100 cm above the “0” datum of the gauge. Due to the increasing recreational and environmental demands, the latter has been lifted to 110 cm in the mid-1990s.



Balaton Lake in Hungary, Figure 1 Lake Balaton and its catchment area.

Early observation of the lake water movements

VITUKI (*Research Institute for Water Resources* as named that time), responsible for the hydrological data collection, established a permanent measuring and research station at *Balatonszemes* in 1962 (Muszkalay, 1965). Besides continuously measuring the local wind direction and velocity, a network of 10 water level recorders has been established around the lake. Collection of wave data were started from a platform resting on piers driven into the lake bed, and the wind-driven water circulation was followed from an anchored vessel using marked buoys. The list and the locations of different hydrological observations are shown in Figure 2, again oriented to north.

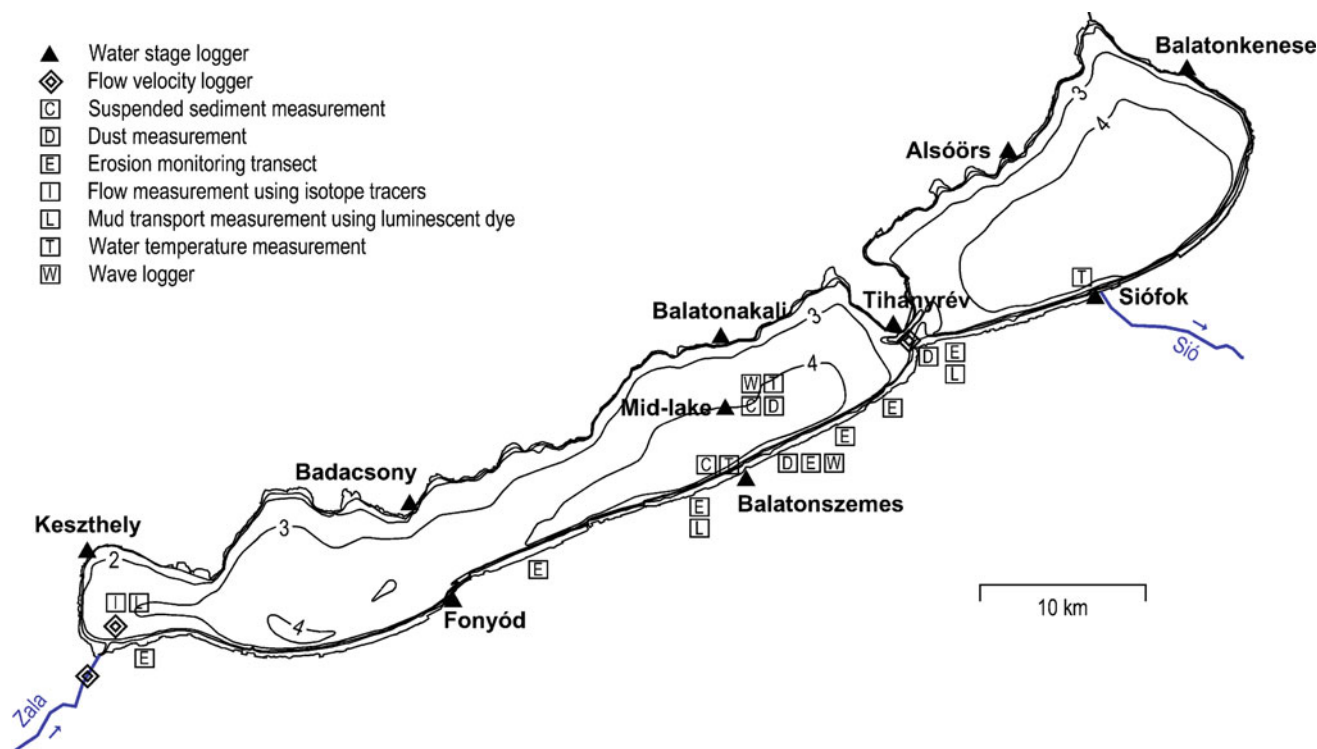
The analysis of long-term wind records of the national meteorological station at *Siófok* showed that the prevailing wind directions are W, NW, and N. From the viewpoint of the denivelations of the water level (seiche), the frequency of SW winds, nearly parallel with the longitudinal axis of the lake, is rather low; however, its observed maximum is about 1.20 m. In the crosswise sense, the seiche is more frequent, and its maximum value is 0.40 m.

Due to its shallowness, the inner circulations of Lake Balaton are generated and maintained mainly by the mentioned movements of the water surface, i.e., by the highly transient wind activity over the lake. Expectedly, the highest flow velocities occur in the Strait of Tihany

(up to 1.40 m/s). In other parts of the lake, the flow velocities vary from 0.10 to 0.40 m/s, depending on their exposure to the wind and on the wind parameters. The hills covering the northern shore of the lake have a significant protective effect against the strongest winds; therefore, in the nearshore zones, significant currents can develop along them. Further results of shallowness are the large gyres, with diameters of several kilometers dividing the lake into big cells, their flow directions being opposite to their neighbors'. These main flow patterns were later generally supported by findings in hydraulic model tests and even by the results of recent numerical modeling.

Hydrodynamic research since the early 1980s

A complex international research project was carried out in *ILASA* (*International Institute of Applied Systems Analysis*), Austria, in the early 1980s with establishing measures to improve lake water quality as ultimate goal. The achievements of the projects (see van Straten and Somlyódy, 1986) were finally based on rather simplified hydrodynamics as limited field measurements could not validate sophisticated 2- and 3-D numerical flow models of that time. In the research projects of the late 1990s, in turn, a fruitful coupling of field measurements, theory, and computer modeling applying up-to-date instrumentation and numerical techniques could be performed

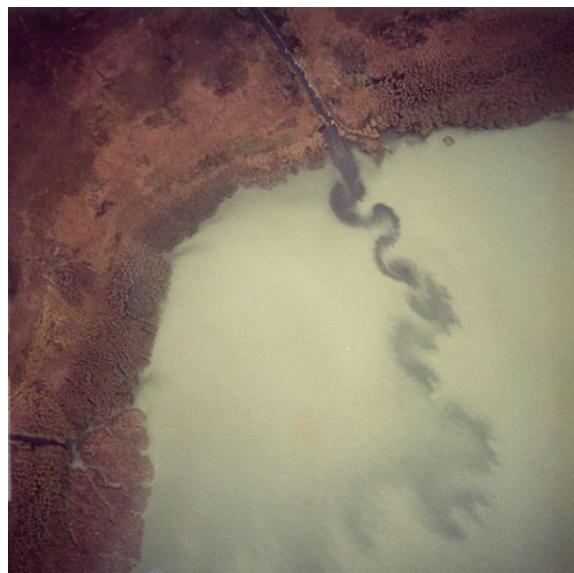


Balaton Lake in Hungary, Figure 2 Hydrometeorological observation network on lake Balaton (1964).

(Józsa et al., 1998). As the projects were carried out in several phases, the experience could be gradually utilized, and research tools as well as methodologies could be upgraded accordingly. Field measurements consisted of simultaneous, long-term, automated recording type of observation of the wind, flow, and turbidity at a number of representative lake sites. In most cases, the campaigns focused only on a particular part of the lake at once. In some phases, special emphasis was put on special issues, e.g., the wind speed variation along the fetch, water exchange at the interface zone of adjacent bays, or the circulation structure in nearshore regions. All the research projects were conducted in cooperation with the *Finnish Environment Institute*, whereas the up-to-date instrumentation was provided by *Aanderaa Instruments*, Norway. In fact, their wind station, propeller as well as Acoustic-Doppler type of current meters, and optical turbidity sensors proved very robust tools in most conditions (Tengberg et al., 2001). Of course, in order to apply them in the given shallow (typically from 1 to 4 m) conditions, special deploying techniques had to be developed.

In numerical model development, the mathematical description of the hydrodynamic and sediment transport processes were based on the traditional conservation laws applied to mass, volume, and momentum (see e.g., Simons, 1980). Starting from the general three-dimensional time-dependent approach, reasonable simplifications could be introduced due to the shallow water conditions. In order to describe the lake-wide water mass transport in most cases, the depth-integrated approach of the wind-driven circulation patterns proved sufficient. Model calibration and verification covered the proper tuning of wind, flow, and sediment transport models. It is important to underline that detailed analysis of the simultaneous wind data and thorough parameter calibration of the relationships resulted in a substantially improved estimation of the wind shear stress field over lakes. The essential of the approach, well known in boundary layer meteorology, but more or less ignored that far in lake circulations, laid in considering the development of a so-called *internal boundary layer (IBL)* downwind of an abrupt change in the surface roughness conditions (see Garratt, 1990, for an review), such as the one at the upwind lakeshore. The improved wind stress field could provide good fitting of calculated and measured flow patterns in a wide range of situations. The coupled measuring-modeling achievements could then provide significantly improved scientific support to decision making on, e.g., thin-layer dredging strategies in the most polluted western bays of the lake.

As to the bay-wide flow features, it was found that, in addition to the impact of uneven bathymetry (known as the origin of the so-called topographic gyres), they are influenced significantly by the non-uniformity of the wind stress field, as a combination of upwind topography (Józsa et al., 1990) as well as IBL development effects (Józsa et al., 2007), the latter playing the more



Balaton Lake in Hungary, Figure 3 Aerial photo of a bay showing the reed belt and the evolution of the brownish plume of a small effluent.

important role. In fact, a semi-analytical parameterization of that in numerical modeling provided an overall reasonable matching between measured and calculated horizontal circulation patterns. Considered in their overall complexity, flow conditions and their impact on mixing are well represented in Figure 3 by the plume of a small creek effluent to a bay, draining brownish water clear from suspended solids while flowing through the littoral reed belt. The plume serves here as a *Lagrangian* indicator of the lake dynamics, consisting of seiche- and circulation-induced advection, as well as wave- and turbulence-induced dispersion, all influencing the suspended solids transport and water quality of the lake, too.

Sediment dynamics

The mineral/chemical composition and the soil physical parameters of bottom sediment are important factors for both the investigation of biology and history of Lake Balaton. The repeated surveys of the lake bottom and the systematic core sampling programs made the estimation of the annual rate of silting possible. It was found that about 8,000 years ago, this was as low as 0.15 mm/year and increased to 0.80 mm/year in the last 1,000 years. The rate of silting up has significantly accelerated in the twentieth century and reached 7–10 mm/year (Szesztay, 1963).

Due to the shallowness of Lake Balaton, the wind-induced waves are reaching the bottom surface frequently. The uppermost 5–8 mm thick layer of the sediment is very loose and can easily be stirred up by wave effect, causing a suspended sediment concentration of about 300 mg/l in the 2–3 m deep water body. The suspended fine sediment

grains are transported with the velocity and in the direction of the water flow, often carrying chemicals from phosphorus to mercury attached to their surface to significant distances where they settle out. The transport process can be followed by placing several settling tubes on different points of the lake bed or suspended within the water body hanging from anchored buoys. The tubes have to be emptied from time to time and the mass of the settled suspended sediment grains determined. From these results, the flux of sediment transport for each tube can be calculated. The location of the highest flux indicates the main direction of suspended sediment transport.

Another way of sediment motion is *creeping* along the bottom in a 1–2-cm thick layer. This way of transport is much slower than in suspension; however, the mass of the moving bottom material is much higher. The estimation of their speed and direction is possible by using tracer methods. In Lake Balaton, having a great recreational value, *luminescent* tracers are used, wherever possible, instead of *radioactive* ones. In the sand, grain-size range artificial tracer grains (ground luminescent glass) were used; in case of silt, a pulverized Chromium-glass powder was produced. Both types of tracers were mixed with natural sand or silt grains respectively and placed to the lake bottom in one or more points. After longer windy periods, bottom samples were collected from the study area and the number of tracer grains counted in them. Furthermore the distance of sampling points from the start usually give enough information about the average velocity and direction of sediment movement. The latter is the more important in lake sediment transport studies because mostly the *direction* of the movement is decisive when the main *sediment scouring* and *accumulation* points or regions are to be determined.

Figure 2 indicates that the first tracer measurements were carried out in the *Keszthely Bay* in as early as 1964, the region heavily inclined to siltation. The field studies revealed the spreading characteristics of sediment brought into the lake by the *Zala River* and proved the existence of a broad stripe of sediment transport toward Keszthely along the wind-protected northern shore of the bay. Another long-term tracer measurement took place near *Balatonszemes* in 1963 where the bank material has been heavily eroded by the waves arriving from N-NW directions. The annual displacement of the luminescent glass grains ground to sand-size fractions demonstrated here the transport of the eroded bank material along the southern shoreline toward *Fonyód* with an average speed of 100–110 m/year. These findings in the early sixties significantly assisted the design of sediment dredging locations in the Keszthely Bay and that of the shoreline protection structures along the reaches mostly exposed to wave erosion.

As a major contribution to the above results, in the research projects of the late 1990s, turbidity data automatically collected simultaneously with wind and flow data were also analyzed. Turbidity sensors were first calibrated against lake bed sediment in lab conditions then jointly

used to estimate suspended sediment mass fluxes. Samples were analyzed to estimate the grain size distribution in different parts of the lake bottom and the water body. A number of sediment collecting tubes, used also earlier, facilitated to determine vertical sediment fluxes in prevailing wind conditions. The analyses confirmed that the bottom sediment often presents the character of cohesive mud due to the large amount of fines, mainly clay. Cohesive sediments, especially when being subject to alternating consolidation and fluidization, need special care both in analysis and modeling. Based on the data analysis, a multi-fraction-suspended sediment transport model was developed to handle different grain size ranges separately rather than looking for one single diameter to represent the whole spectrum. To identify zones with various sediment dynamic parameters, a detailed penetrometer surveying of the study was also carried out. By means of all this, it became possible to reproduce the selective bottom erosion and deposition processes resulting in large bay- and lake-wide irregularities in the bottom sediment distribution. Such modeling tools have been utilized to support a number of projects to perform dredging and improve water quality since then.

Conclusion

Based on the pioneering measurements and observations of the 1960s and 1970s and to the rapid development of instrumentation and informatics starting in the 1980s, in 1990s significant progress was achieved in understanding and simulating the decisive parameters of the most important hydro- and sediment dynamic processes of Lake Balaton. The maintenance of the hydrological, chemical, and biological balance of the lake and the design of yacht marinas have mostly profited from the research results.

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BALTIC SEA BASIN, SINCE THE LATEST DEGLACIATION

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Introduction

The Baltic Sea basin is one of the world's largest intra-continental basins, occupying 373,000 km² with a drainage area four times its size. Its mean depth is c. 54 m, although a few relatively deep basins exist, e.g., the Eastern Gotland basin (248 m) and the Landsort Deep (459 m) (Figure 1). The Baltic Sea basin has served as a depositional sink throughout at least the last several hundred thousand years, and its sediments comprise a unique high-resolution archive of the paleoenvironmental history of the huge drainage area, the basin itself, and neighboring sea areas. These sediments also constitute the base for the reconstruction of the Baltic Sea basin since the Last Glacial Maximum about 20,000 years ago, and the development of the Baltic Sea basin since then has been controlled by land uplift, the result of the down pressing of the crust from the Scandinavian ice sheet, and the fluctuations in the global sea level. This has resulted in what we can distinguish as several developmental stages of the Baltic Sea basin, both freshwater and brackish water stages, alternatingly, namely the Baltic Ice Lake stage, the Yoldia Sea stage, the Ancylus Lake stage, and the Littorina Sea stage. Despite the fact that the Baltic Sea basin has a fairly long history, the present Baltic Sea is a stage in the development since the Last Glacial Maximum, which is a relatively short time from a geological perspective.

The Baltic Ice Lake stage

The oldest stage in the history of the Baltic Sea began when the Scandinavian ice sheet started to melt and the ice margin retreated northwards. As the ice sheet retreated from the southern Baltic Sea basin, it left an environment probably comprising several small melt water lakes dammed between huge areas with grounded icebergs and blocks of dead ice that had broken off from the retreating ice margin. This is how we believe the

environment was in the southern Baltic Sea basin some 15,000–16,000 years ago (Houmark-Nielsen and Kjær, 2003).

In front of the retreating ice margin c. 14,500 years ago, a large, continuous melt water lake formed, the Baltic Ice Lake, which had an outlet through the Öresund strait. After about 500 years the erosion of Öresund strait reached down to the bedrock threshold, located at 7 m depth, which stopped further erosion. Land uplift of the ice-free southern Sweden raised the threshold over the ocean level and the outlet could be described as a giant waterfall. Differences in the land uplift south and north of the sill area resulted in a rise of the Baltic Ice Lake water level in areas south of the outlet, in southern Denmark, Germany, and Poland. In the newly ice-free areas north of the Öresund strait, land uplift was so strong that no rise of the shoreline has been registered.

About 14,000 years ago the ice margin ran from south central Sweden relatively straight east over the Baltic Sea basin and to central Estonia.

The ongoing melting led to more water being added to the Baltic Ice Lake, but its surface was relatively stable since the threshold at Öresund acted as an overflow. Then, about 12,800 years ago, the shorelines suddenly fell in eastern Småland by about 5 m and by as much as 10 m in Blekinge (Björck, 2008). This means that the Baltic Ice Lake sought a new outlet for a relatively short period.

The location of this outlet has been the subject of much debate among Nordic geologists, and connections between the Öresund strait and the Baltic Sea basin or the White Sea have been proposed but found unlikely. The most likely scenario seems to have been an outlet through southern central Sweden. A model has been developed where the ice edge retreats a short distance north from Mount Billingen's northern tip and thus opens a connection between the Baltic Ice Lake and the North Sea (Björck and Digerfeldt, 1984).

In the sediments from this time there are no signs that salt water entered the Baltic Sea basin, which indicates that this connection only existed for a short period and served only as an outlet for the Baltic Ice Lake. As result of this lowering of Baltic Ice Lake surface, for the first time since the ice sheet began to melt a land bridge formed between southern Sweden and the continent, which must have facilitated the migration of plants, animals, and humans.

The climate warming that had been ongoing since the ice sheet began to melt was interrupted by an approximately 1,300-year long cold period (Younger Dryas) that began about 12,900 years ago. It is possible that the drainage of Baltic Ice Lake together with the drainage of the giant Lake Agassiz in North America contributed to this cold period. The large amounts of freshwater from these two ice lakes might have disturbed the North Atlantic deep water circulation significantly, thus resulting in a cooler climate. The ice sheet began advancing southwards and the outlet at Billingen was closed by the advancing ice.



Baltic Sea Basin, Since the Latest Deglaciation, Figure 1 Map of the Baltic Sea and its surroundings. The numbers refer to sites mentioned in the text. 1 = Landsort Deep; 2 = Eastern Gotland Basin; 3 = Öresund strait; 4 = Småland; 5 = Blekinge; 6 = Mount Billingen; 7 = Bornholm; 8 = Arkona Basin; 9 = Bornholm Basin; 10 = Hanö Bay; 11 = Stockholm; 12 = Gotland; 13 = Lake Mälaren; 14 = Svea River/Svea Falls; 15 = Lake Vänern; 16 = Göta River; 17 = Steinelve/Otteid strait; 18 = Darss Sill; 19 = Dana River; 20 = Great Belt; 21 = Öland; 22 = Södertörn.

As a result, the Baltic Ice Lake water level started to rise up to the level of the Öresund strait threshold and southern Sweden experienced rising shorelines. The ice-free areas north of the Öresund area had a stable or slightly falling water level. These differences are due to land uplift occurring at different rates. In the south, the uplift was slower than the Öresund strait threshold, whereas in the north it was faster.

The elevation of the shoreline in the south began about 12,500 years ago and resulted in the water level of Baltic Ice Lake coming to be level with or slightly above the

threshold in the Öresund strait, a condition that seems to have prevailed over the rest of the Baltic Ice Lake's existence (Figure 2).

At the end of the cold Younger Dryas event the ice sheet once again began to melt more than it grew and the front retreated northward. This meant that the Baltic Ice Lake came to an abrupt end when the ice front for a second time left the northern tip of Mount Billingen and the connection between the Baltic Sea basin and the North Sea re-opened. The level of the Baltic Ice Lake dropped very quickly, perhaps only over a year or two, almost 8,000 km³ of fresh



Baltic Sea Basin, Since the Latest Deglaciation,
Figure 2 Palaeogeographic map showing the Baltic Ice Lake immediately prior to its maximum extension and final drainage about 11,700 years ago.

water was released and the water level dropped by 25 m (Strömberg, 1992; Jakobsson et al., 2007). To get an idea of how much freshwater entered the North Atlantic it can be compared to today's Baltic Sea, which holds approximately 21,000 km³ of water. This happened about 11,650 years ago (Andrén et al., 1999, 2002). The short pulse of freshwater can be detected in sediment cores on the Swedish west coast and further out in the Skagerrak (e.g., Miller, 1982; Erlenkeuser, 1985; Bodén et al., 1997). However, it seems as if it had only a small effect on the circulation in the North Atlantic.

This drainage marks the end of the Baltic Ice Lake and the start of the next stage, the Yoldia Sea stage.

The Yoldia Sea

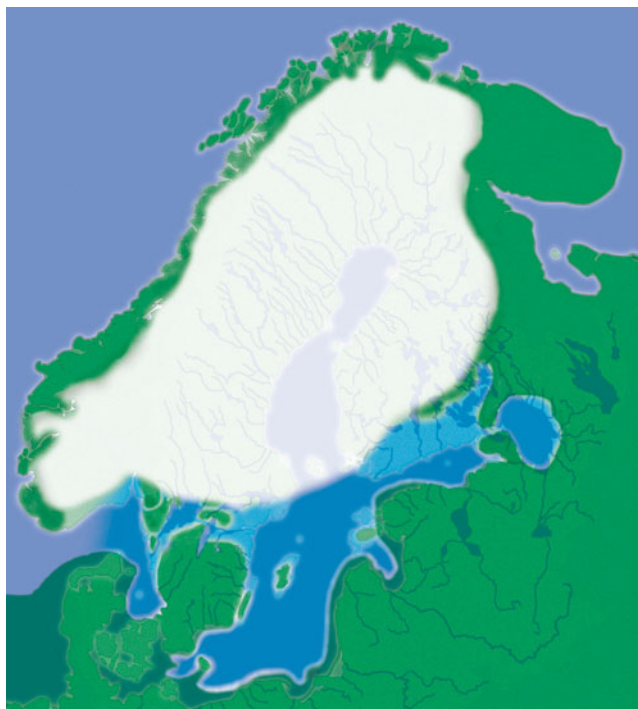
The final drainage of the Baltic Ice Lake at Mount Billingen occurred just before a very exciting time in climate trends since the last glaciation. It was the transition from the cold Younger Dryas to the warm Preboreal about 11,700 years ago. The temperature rise may have been as high as 12° in just 50 years, and this obviously had consequences for the Scandinavian ice sheet covering parts the Baltic Sea basin in several ways. Much more melt water was produced than in the past, and this resulted in an increasing volume of water flowing out of the basin; therefore, no salt water inflows occurred during the first 250 years after the opening of the passage westwards.

Furthermore, as consequence of the increased melting of the ice sheet, its front retreated northwards much faster than before. In connection with this great drainage and the lowering of the Baltic Ice Lake surface by 25 m, as much as 70,000 km² of new land was created. These earlier lake beds consisted of very unstable sediments. Reworked by waves and bottom currents these sediments were redeposited on the Yoldia Sea bottoms and mixed with the sediments that were transported by the melt water from the retreating ice sheet. This resulted in thicker glacial varves being deposited during the early Preboreal time than during the Younger Dryas.

The new low level of the Yoldia Sea immediately after drainage meant great change for the southern Baltic Sea basin. Among other things, the former outlet through Öresund strait closed and a wide land bridge formed between Sweden and Denmark. The major Danish islands came to form a contiguous landmass directly connected with Germany. The island Bornholm was associated with the German mainland via a land bridge, and the German and Polish coastlines were located much further north than today. In Arkona Basin, Bornholm Basin, and in Hanö Bay the shoreline at this time was located at a level 35–50 m lower than today. In Hanö Bay we still can find today stumps on the sea bottom as a reminder of the pine trees that once grew on these low levels.

About 11,300 years ago salt water from the North Sea flowed into the Baltic Sea basin during a period of no more than a maximum of 300 years (Andrén et al., 2007). There are at least two explanations for why it happened at just this time. First, the continued retreat of the ice sheet led to a much wider passage through straits in south-central Sweden, which of course facilitated the inflow of salt water. Second, this period coincided with a small decline in the climate, which had become much warmer after the drainage of the Baltic Ice Lake. This drop in temperature, referred to as the Preboreal Oscillation, may in turn have resulted in the amount of melt water produced by the ice sheet decreasing. This allowed the salt water from the North Sea to penetrate into the Baltic Sea basin. The salinity of the Baltic Sea during this phase of the Yoldia Sea caused the glacial clays deposited during this time to be only weakly varved clay as a result of the flocculation of clay particles in the salt water environment (Andrén et al., 2002).

The nutrients the inflowing saltine water brought into the basin resulted in the production of both zoo- and phytoplankton for the first time after the deglaciation. This is visible as a small increase in the amount of organic carbon in sediments. Fossil shells of mollusks, ostracods and microscopic plant plankton (diatoms) are found in the clays from this stage (Andrén and Sohlenius, 1995; Wastegård et al., 1995; Andrén et al., 2000a). This stage in the development of the Baltic Sea is named after fossil findings of the arctic mollusk *Yoldia arctica* (nowadays renamed *Portlandia arctica*). Black bands of monosulfides in the sediment deposited at the sea bottoms of the Yoldia Sea indicate that a salinity



Baltic Sea Basin, Since the Latest Deglaciation,
Figure 3 Palaeogeographic map showing the Yoldia Sea at the end of the brackish phase about 11,100 years ago.

stratification was developed, preventing the water masses that mix vertically, which leads to oxygen deficiency on the bottoms. Other examples of fossils in the clays deposited in the Yoldia Sea are almost complete skeletons of both harp seal and ringed seal in central Sweden. There are also reports on the findings of a cod fish, probably whiting, in a clay pit in the Stockholm area (De Geer, 1913). After studies of the fossil diatom flora we know that this brackish phase of the Yoldia Sea ended about 11,000 years ago and that at this time the surface water throughout the basin was slightly brackish, much like in today's Gulf of Bothnia (Andrén et al., 2000a, 2002) (Figure 3).

In sediments that are 100 years younger, we find no trace of a brackish environment (Andrén et al., 2000a). The ongoing uplift of the straits in south central Sweden led to the passage becoming narrower and, as a result, salt water inflows decreased, which led to a freshening of the Yoldia Sea. In the Lake Vänern basin, which was part of the Baltic Sea basin, however, we can see traces of marine influence for the remainder of the Yoldia Sea stage. With time, however, the straits in south central Sweden became so narrow and shallow that the Yoldia Sea water level began to rise in pace with the uplift of the straits. The first signs of a rising shoreline in the southern Baltic Sea basin and the next stage of the Baltic Sea development began 10,700 years ago. To summarize the Yoldia Sea stage, it

started out as a melt water lake during the first 350 years of existence, followed by a short phase of brackish water conditions and after 300 years it turned back to freshwater conditions. Although this 1,000-year stage of Baltic Sea development was, for the most part, characterized by freshwater, a somewhat illogical historical division of the Baltic Sea stages, with the lake and sea stages, has been retained. The short time that seawater flowed into the Yoldia Sea has apparently been important for the development of biological life in Baltic Sea basin.

The Ancylus Lake stage

During investigations on the island of Gotland at the end of 1800s, Swedish geologist Henrik Munthe found fossils of the freshwater snail *Ancylus fluviatilis* in sediment layers located between the layers from the weakly brackish Yoldia Sea and the brackish Littorina Sea. This gave him evidence of a new freshwater stage of Baltic Sea development. However, it was Gerard De Geer who later gave this Ancylus Lake stage its name. More recently, in further analysis done on the sediment layers containing *Ancylus fluviatilis* the proposed freshwater environment has been confirmed by findings such as a fossil freshwater diatom flora. Both *Ancylus fluviatilis* and the recorded siliceous microfossils exists today, the snail in rivers and the diatoms in lakes such as Lake Mälaren.

The Ancylus Lake stage remains the least known of the Baltic Sea stages and most difficult to understand the evolution of.

In the early 1900s it was discovered what was assumed to be Ancylus Lake outlet westwards, and it was named the Svea River. By studying the older shorelines, raised by the uplift, it was assumed that the Ancylus Lake water level was between 15 and 30 m higher than that of Lake Vänern in west. It was then concluded that the outlets of the river were a series of powerful waterfalls, the Svea Falls, in the northeastern part of the Lake Vänern basin. More modern research has found clays of Yoldia Sea age in the supposed discharge area and consequently no erosion has occurred during Ancylus Lake time. It can thus be concluded that the water depth in this area must have been significant at this time and that Lake Vänern was part of Ancylus Lake and became isolated from the North Sea at about the time the Ancylus Lake water level began to rise. The Ancylus Lake was then dammed with a water level above the North Sea area, but its outlet must be found west of Lake Vänern. Today we believe that the outlets were located in the Göta River and Steinälva/Otteidstrait, and that the Ancylus Lake water level began to rise when the uplift of these outlet areas made both of them narrower and shallower.

As a result of the fact that the land uplift was greater in the areas in north where the ice sheet just recently melted, the Ancylus Lake level came to rise rapidly in the southern part of the Baltic Sea basin where the uplift was slowing down. In the very southern Baltic, submerged pine trees and peat deposits dated to between 11,000 and 10,500 years ago are evidence of a transgression



Baltic Sea Basin, Since the Latest Deglaciation,
Figure 4 Palaeogeographic map showing the Ancyclus Lake during the maximum transgression about 10,500 years ago.

(Andrén et al., 2007) (Figure 4). The rise of the water level in this area may have been as fast as 5–10 cm a year. The total increase of the water level in this area was as much as 25 m and the rise continued until about 10,300 years ago, when its highest level was reached. One result of this rapid increase of the water level was that the pine trees that grew in Hanö Bay came to be drowned in just few 100 years.

North of a line running from the southern Lake Vänern through south central Sweden and further eastwards across the Baltic Sea towards the Finnish south coast, no records of a rising Ancyclus Lake water level are to be found, as land uplift is the dominant process in these areas.

The Ancyclus Lake water level in the southern Baltic Sea basin came to be at least 10 m above the North Sea's present sea level, but in less than 200 years its level was lowered to sea level at the time (Björck et al., 2008). How did this happen?

The traditional view has been that a southern threshold in the Darss Sill area in the southern Baltic Sea basin was flooded and began to erode. The Ancyclus Lake could then drain into the Kattegat through the Great Belt and its surface was lowered to the level of the North Sea. This drainage system has been called the Dana River (von Post, 1929). The reason for a drainage system like this is the difference in the uplift of the Öresund strait, which has served as outlet before, and the Darss Sill area shifted

the lowest point southwards to northern Germany. It has further been thought that when the outlet in the south started the initial outlets through central Sweden were still active, but they should have closed relatively quickly when the lowering of the lake level was so quick. The shallower these initial outlets become, the more water must be drained via the Dana River. There are also deposits on the seabed of the Great Belt, which indicates both high material transport and high current speeds (Novak and Björck, 1998). A great Dana River, as outlined above, has been proven unlikely as the threshold on the sea bottom in the Darss Sill area is too shallow (e.g., Bennike et al., 1998; Jensen et al., 1999; Lemke et al., 1999; Lemke et al., 2001). Today, it is believed that the southern outlet of the Ancyclus Lake was characterized by a variable fluvial environment, creating fluvial, levee, and lacustrine deposits, i.e., more of a calm water environment than a river-type water flow (Björck et al., 2008).

As a consequence of the new outlet in the south, the Danish so-called mainland time was over and the initial spillway through central Sweden became dry and, for the first time since the ice sheet melted, there was a land bridge between the southern and northern Sweden created.

Although today we are not entirely clear on where the Ancyclus outlet was located and configured, we know that its surface was level with North Sea about 10,000 years ago, and that the outlet must have existed somewhere in the south. The rising sea level at this time resulted in weak, short, and sporadic pulses of inflowing marine water, starting some 9,800 years ago and passing through the same pathway. This can be seen in the composition of the fossil diatom flora in sediments from both Bornholm Basin and along the Blekinge Coast (Andrén et al., 2000b; Berglund et al., 2005). The same inflows were also recorded in sediments from eastern Gotland Deep, but much weaker than in the Bornholm Basin (Andrén et al., 2000a). This suggests that influx emanated in the southernmost part of the Baltic basin. In the southern Baltic, these inflows mark the beginning of the next stage in the development of the Baltic Sea, but for the central and northern Baltic Sea, it took another 1,000 years before the salt water inflows became so strong and long-lasting that these areas were affected.

The Littorina Sea stage

When the climate became warmer and the last glacial period ended, the Earth's ice sheets began to melt. The melt water was added to the oceans and the global sea level began to rise, at times by as much as 2 cm/year. About 10,000 years ago, a connection between the Baltic Sea and the oceans was established and marine water started to flow into the Baltic Sea. These inflows occurred through the passages that are still active today for water exchange with the North Sea, i.e., in the beginning Great Belt and later also the Öresund Strait. This is the beginning of a 2,000-year-long period of relatively low and fluctuating salinity in the southern Baltic

Sea (Andrén et al., 2000b); a transitional period in Baltic Sea development is sometimes referred to as the Mastogloia Sea.

When the contact between the Baltic Sea and the oceans was established, the water level around the Baltic Sea rose due to the local land uplift and the rising sea level. In the southern part of the Baltic Sea basin this meant a rising sea level – a so-called transgression – which led to even more abundant inflow of salt water. About 8,000 years ago the water depth at Öresund was similar to today, and in the southern Baltic Sea the salinity was approximately the same as today. After another 500 years, brackish water conditions also prevailed in the central Baltic Sea. Sediments from the German coast deposited during this time contain fossil shells of the marine snail *Littorina littorea*. This snail has also given its name to this stage of the Baltic development, Littorina Sea.

The continued rise in global sea level meant that the depth of water in the Öresund and Great Belt became greater than today, and in the Baltic Sea the first so-called Littorina transgression was started. It culminated 6,500 years ago when the Littorina Sea level was about 5 m above today's sea level in southernmost Sweden (Figure 5) (Berglund et al., 2005; Yu et al., 2007).

A fluctuating sea level is something that seems to have characterized the southern Baltic Sea during Littorina Sea stage. Today the best way to study these sea level changes

is along the southern Baltic Sea coasts, where land uplift during the Littorina Sea period was small and the dominating component in shoreline changes was change in sea level. There are up to six different transgressions recorded in sediments of the Littorina Sea stage age (Berglund et al., 2005). Even on the islands of Öland and Gotland, along the coast of Småland (Svensson, 1991), at Södertörn (Risberg, 1991), and in the south of Finland the Littorina Sea transgression are documented. Along the coasts of the Bothnian Sea and the Gulf of Bothnia there is no transgression registered, since the land uplift in this area throughout Littorina Sea stage was greater than the sea level rise.

As the marine- and nutrient-rich water started to flow into the Baltic Sea basin, algae and phytoplankton began to thrive. Large amounts of organic material from dead organisms were deposited on the sea bottom where the oxygen was consumed during decomposition. Approximately 7,500 years ago, laminated sediments were deposited over large bottom areas in the central Baltic Sea, which means that the bottoms had completely oxygen-free conditions and no burrowing organisms could live there (Sohlenius and Westman, 1998; Andrén et al., 2000a; Sohlenius et al., 2001; Zillén et al., 2008). So-called “dead bottoms” were created. This also suggests that the vertical water mixing was missing, indicating the presence of salinity stratified water masses, a halocline was established. Conditions like this are very similar to today's Baltic Sea bottom conditions. An additional 1,000 years later these conditions also prevailed in the Bothnian Sea and Bothnian Bay.

We also know from studies of these laminated sediments that blue-green algal (cyanobacteria) blooms were common in the early Littorina Sea stage (Bianchi et al., 2000; Borgendahl and Westman, 2007). They might even have been stronger than today's much-discussed blooms. This can be determined from the sediment's preserved pigment residues from cyanobacterial algae. Such fossil pigment residues have been found in sediments from both the southern and central Baltic Sea. Sediments from the Bothnian Sea and Bothnian Bay have not yet been investigated, but blooms may have been occurring there also during this time. Conditions during the early Littorina Sea times, with high temperature, relative calm, low salinity (blue-green algae require a salinity of no more than 11.5%), and small competition with other algal groups (such as diatoms, which are found very sparingly in the sediments deposited during this time), apparently favored these blooms.

From the fossil diatom flora we know that the salinity of the Baltic Sea about 6,000 years ago was higher than today (Andrén et al., 2000a, b). This may have been an effect of a larger inflow of marine water through the straits in the south, probably a greater evaporation due to a higher insulation during summer and lower inflow of freshwater by the rivers. We currently do not know exactly how much higher salinity the Littorina Sea had. Results from studies of oxygen isotopes in fossil shells from the Gulf of



Baltic Sea Basin, Since the Latest Deglaciation,
Figure 5 Palaeogeographic map showing the Littorina Sea during the most saline phase at about 6,500 years ago.

Finland, however, indicate about 4% higher salinity than today (Donner et al., 1999).

The time when the salinity of the Baltic Sea was highest coincides with the warmest time since the last Ice Age, the so-called postglacial climate optimum. At that time trees such as oak, linden, and elm, which required a warm climate, grew in southern parts of northern Sweden. Since this time, the salinity of the Baltic Sea decreased to present-day levels, and it is said that the actual Littorina Sea stage ended 3,000 years ago. The climate also became colder, except during the Medieval Warm Period. This was a warm period that occurred 900–1300 AD, and it is known that the Scandinavian Vikings settled in Greenland and that grapes species grew in England that today grow in northern France. For the Baltic Sea it meant that, once again, times of high production of algae and phytoplankton. Once these fell to the sea bottom, the oxygen was consumed, anoxic bottom conditions prevailed, and the areas displaying laminated sediments increased (Andrén et al., 2000a; Leipe et al., 2008). It also appears that intense blue-green algae were common during this time. This warm period was followed by a colder one, the so-called Little Ice Age. This cold phase also resulted in warm-demanding diatoms species disappearing from the Baltic Sea flora, and they have not reappeared since (Andrén et al., 2000a, b).

The present Baltic Sea

The latest 1,000 years of Baltic Sea development, with a salinity similar to today's, has sometimes been called *Mya* Sea, after the North American sand clam *Mya arenaria*. They may, in their larval stage, have been transported in ballast water of merchant ships into the Baltic Sea. It was previously believed that the species came over from North America when the Atlantic races started in the 1500s. Danish colleagues have shown using radiocarbon dating of the earliest *Mya* shells that they are of Viking age (Petersen et al., 1992). Further evidence that the Vikings were in North America long before Columbus!

Ever since humans began to use the land around the Baltic Sea they have interfered with the natural environmental evolution. One old example of this is the occurrence of specific lead isotopes emanating from human lead use and atmospherically transported and subsequently deposited in the Baltic Sea sediments. This dates back to as early as when the major use of lead shifted from the Iberian peninsula to Germany, the French alps, and the British Isles in the first to third centuries AD (Bindler et al., 2009).

Even though it cannot be expected that the Baltic Sea a 100 years from now will look the same as the present Baltic Sea as a result of ongoing natural phenomena, it must be stressed that the present pressure put on its ecosystem by humans is much larger than the natural processes involved.

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BASIN-SCALE INTERNAL WAVES

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Definition

Basin-scale periodic waves propagating on a thermocline or other subsurface density interface.

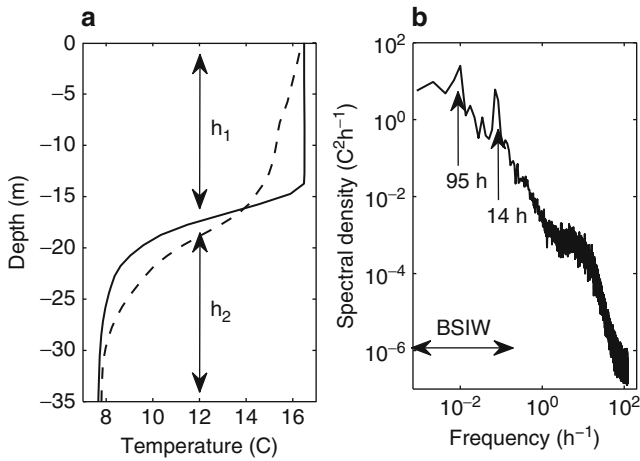
Introduction

The complex hydrodynamic processes in lakes mainly result from a competition between surface heat flux and wind stress. While the former sets up stabilizing density stratification during summer and winter (beneath ice cover), the action of the latter, on the stratification, leads to internal waves of various temporal and spatial scales that drive irreversible turbulent mixing. Roughly 20% of the wind energy entering the lake is transferred to large-scale wave motions, called basin-scale internal waves (hereafter BSIW) – the remainder being dissipated in the surface layer. These waves temporarily store the wind energy until it is dissipated, mainly by friction along the lake bed. They play a crucial role in the transport of mass and momentum in the lake, driving horizontal dispersion and vertical mixing with great implications for biogeochemical processes and contaminant transport. This article quantitatively describes BSIW dynamics, with particular illustrations from Lake Simcoe (Canada), and provides a framework for the reader to recognize and analyze BSIWs in observational data.

BSIW are characterized by the basin shape, the stratification (See [Stratification in Lakes](#)), and the influence of the Earth's rotation. Typical periods of BSIW range from days to hours ([Figure 1b](#)) and are long compared to periods of surface seiches, which have periods of minutes to hours, and wind waves, with periods of seconds.

Generation of basin scale internal waves

To describe the generation of these waves, we start with a simple rectangular lake of length, L , width, B , and depth, H , with a sharp thin thermocline separating a homogenous warm epilimnion of thickness h_1 and density ρ_1 and from a homogeneous cold hypolimnion of thickness h_2 and density ρ_2 ([Figures 1a](#) and [2a](#)). A steady wind applied to the lake surface ([Figure 2a](#)) causes an upwelling (setup) of the free surface and a downwelling of the thermocline at the downwind shore. If the wind forcing lasts for more than a quarter of the fundamental mode-one BSIW period (defined below), the thermocline tilt will span the entire basin with a maximum amplitude $\eta_o = \frac{Lu_*^2}{g'h_1}$, where $g' = g(\rho_2 - \rho_1)/\rho_2$ is the reduced gravity as a result of the density difference across the thermocline. The wind stress on the surface is captured by the shear velocity $u_* = \sqrt{\rho_a/\rho_1 C_D W_{10}^2}$, where the wind, W_{10} , is



Basin-Scale Internal Waves, Figure 1 (a) Typical summer temperature profile in Lake Simcoe. The solid line represents a profile where the two layers assumption is valid. The dashed line profile allows more than vertical mode-one with a continuous stratification. (b) Power spectra of thermocline displacement from a temperature chain mooring located in Lake Simcoe, showing basin-scale internal waves with periods of $T = 95$ h and $T = 14$ h. These periods vary during the season with the change in stratification. (D. Bouffard and L. Boegman, unpublished). Raw temperature data provided by D Evans.

measured 10 m above the lake surface, and $\rho_a = 1.2 \text{ kg m}^{-3}$ is the air density and $C_D \sim 10^{-3}$ is a drag coefficient (Figures 1 and 2).

The gravitational force acting on the tilted interfacial free surface and thermocline generates both surface (barotropic) and internal (baroclinic) pressure gradients, which balance the applied wind force. When the wind stops, the gravitational force is unbalanced and the interfaces relax, generating freely propagating basin-scale internal and surface waves, from both upwind and downwind ends of the lake. The upwind and downwind components combine to form basin-scale standing waves on both interfaces, referred to as surface and internal seiches (See *Internal Seiches*).

A single wind burst or aperiodic wind events lead to free modes with natural periods that depend on the basin shape, the stratification, and the Earth's rotation. Conversely, periodic wind forcing (e.g., sea breeze) systematically resets the phase of the wave, leading to forced BSIWs with periods that match those of the wind forcing (e.g., Lake Kinneret, Gomez-Giraldo et al., 2006).

Horizontal pattern of BSIW

A two-layer system is a good approximation for most lakes at mid-latitude during the late summer (Figure 1a), and we treat the horizontal distribution of BSIW in this case. When the wind relaxes, the oscillation takes the form of a sinusoidal standing wave with antinodes at either end of the basin. The motion is described by the linear shallow water equation, the wave speed $C = \sqrt{g'H_e}$, where

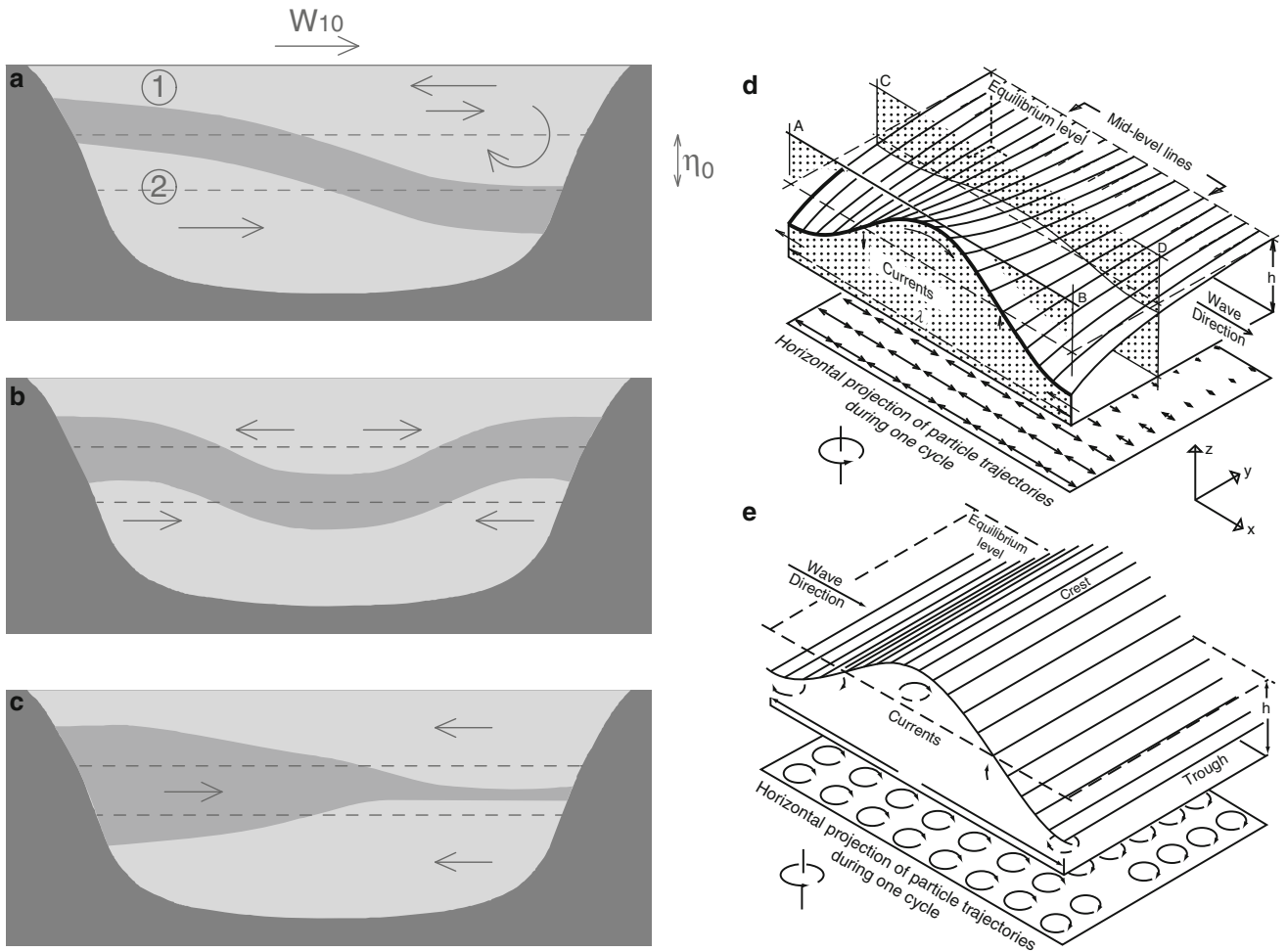
$H_e = h_1 h_2 / (h_1 + h_2)$, the equivalent depth. C depends on the stratification and will change during the season as the thermocline deepens. Different horizontal wave modes can be excited, in the lake, as long as they match the antinodal boundary condition (Figure 2b), and the different periods associated with the horizontal modes are $T_n = 2L/nC$, where n is the number of nodes in the horizontal (i.e., the horizontal mode). The periods of the waves are thus dependant on the stratification (through C) and the basin size, potentially tuning the BSIW into and out of resonance with periodic wind forcing (Antenucci and Imberger, 2003). The first horizontal mode can contain up to 98% of the energy embodied in the initial wind-induced thermocline tilt, but basin shape and/or wind forcing can enhance the importance of secondary modes in some cases (Münnich et al., 1992; Boegman et al., 2005).

Vertical pattern of BSIW

A diffuse seasonal thermocline (metalimnion) with a continuous stratification (Figure 1a dashed line), or the presence of both seasonal and diurnal thermoclines, allows vertical basin-scale modes to be generated in addition to the horizontal modes. The wave motions are described by the Storm-Liouville eigenvalue equation (Gill, 1982; Mortimer, 1974), which is typically solved numerically to obtain a set of phase speeds corresponding isotherm displacements (wave functions) for possible vertical modes. The most energetic mode is generally the vertical mode-one, where currents oscillate in the opposite directions in the epilimnion and the hypolimnion inducing a significant shear through the thermocline (Figure 2a). Higher vertical modes are usually due to an upwind-downwind asymmetry in the tilting and are found to become dominant when their period is resonant with the wind period, $T_{n,m} = 2\pi(1 + (mL/nH)^2)/N$, where m is the vertical mode, $N^2 = -(\frac{g}{\rho})(\frac{d\rho}{dz})$ is the Brunt-Väisälä frequency, and z is the vertical coordinate direction. The vertical mode-two wave is characterized by an expansion and subsequent compression of the metalimnion generating a thermocline jet in the opposite direction as the current in the epilimnion and the hypolimnion (Figure 2c). The vertical mode-one seiche will have a strong impact on the bottom boundary biogeochemical dynamics (e.g., sediment resuspension) as it flows along the lake bed, while the vertical mode-two seiche will affect mixing and biogeochemistry through the thermocline (e.g., phytoplankton maximum, oxygen flux).

Effects of the earth's rotation

In large lakes, the Coriolis force, resulting from the Earth's rotation, becomes significant and can modify the wave pattern. The relative importance of the Coriolis force is quantified with the Rossby radius, $Ro = C/f$, and the Burger number, $S = \frac{Ro}{R}$, where $f = 4\pi/T \sin \theta$ is the Coriolis parameter, $T = 1$ day is the period of rotation of



Basin-Scale Internal Waves, Figure 2 Sketches of (a) horizontal mode-one vertical mode-one, V1H1 internal seiche, (b) horizontal mode-two vertical mode-one, V1H2, and (c) horizontal mode-one vertical mode-two, V2H1. Dashed lines represent thermocline at rest. Dark gray color represents the thermocline separating the warm epilimnion (1) and the cold hypolimnion (2). Thin arrows show the direct response of the lake to wind stress. Thick arrows show the wave-induced currents after the wind. (d) Kelvin wave traveling in the x direction with the shore located to the right. The amplitude of the Kelvin wave decreases exponentially offshore as $\eta = \eta_0 e^{-y/R_0} \cos(kx - \omega t)$. (e) Poincaré wave in an infinite basin. Inertial circles are shown beneath the wave. Panels (d) and (e) are reprinted from Mortimer (1974).

the Earth, θ is the latitude, and R is a typical lengthscale characterizing the basin length or width (usually $L/2$). For lakes with $R > R_0$, $S < 1$ and rotational effects are expected. Conversely, in the case $S > 1$, rotational effects can be neglected.

We illustrate the effects of rotation on BSIWs by considering its influence on a longitudinal internal seiche in a large northern hemisphere lake. As the wind-displaced thermocline relaxes, and the seiche begins to propagate across the basin, the Coriolis force pushes the wave toward the right, where it is bounded by the shoreline, causing it to propagate cyclonically (counterclockwise in the northern hemisphere) along the shore with the wave amplitude decaying exponentially in the offshore direction (Figure 2d). This wave is called a Kelvin wave, and its

period must be greater than the local inertial period, $T_i = 2\pi/f$. The phase velocity and corresponding wave period, T_l , remain the same, for the Kelvin wave, as in the non-rotational case. At a distance of $2R_0$ offshore, the wave is only 10% of its maximum amplitude, so in very large lakes, such as the Laurentian Great Lakes, where $R \gg R_0$, the Kelvin wave is a nearshore phenomenon that takes the form of a coastal jet. In smaller lakes, where $R \sim R_0$, the Kelvin wave signature can be found throughout the basin (e.g., Lake Simcoe).

We now consider the effect of rotation on the transverse basin-scale internal seiche. Because $L > B$, contrary to the longitudinal seiche, the transverse seiche is not constrained by the boundaries at the longitudinal ends of the lake. When deflected to the right, by the Coriolis

force, the seiche is, therefore, modified into a progressive anticyclonic (clockwise in the northern hemisphere) waveform. Fluid particles displaced by the wave follow anticyclonic circular or elliptical trajectories (Figure 2e), known as inertial circles, with radius $r_i \sim u/f$, where u is the wave-induced current speed. These transverse waves are called inertia-gravity waves or Poincaré waves, and the dispersion relation for a rectangular basin, in terms of the wave period, is given by: $1/T_{PW}^2 = 1/T_i^2 + (1 + r^2)/T_1^2$, where $r = B/L$ is the basin aspect ratio at the thermocline depth (Mortimer, 2004). The dual character of this wave can be seen in the dispersion relation, where the first term on the right-hand side describes the inertial behavior of the inertial circles, and the second term has gravitational wave behavior with rectilinear motion. This explains the elliptical pattern of the Poincaré wave with the eccentricity depending on the relative intensity of these two terms. The dispersion relation (above) shows that the Poincaré wave period is typically close but always lower than the inertial period, the shift being a function of the basin shape (through r) and the stratification (through T_1) and can therefore be expressed as a function of S (Antenucci and Imberger, 2001) with the same trend of T_{PW} approaching T_i (inertial wave behavior) as S decreases (i.e., large lake).

In large lakes, the coastally trapped Kelvin wave has the strongest wave currents near and running parallel to the boundary (Figure 2c), where the thermocline intersects the lake shore. Here, the Poincaré wave signal is weak

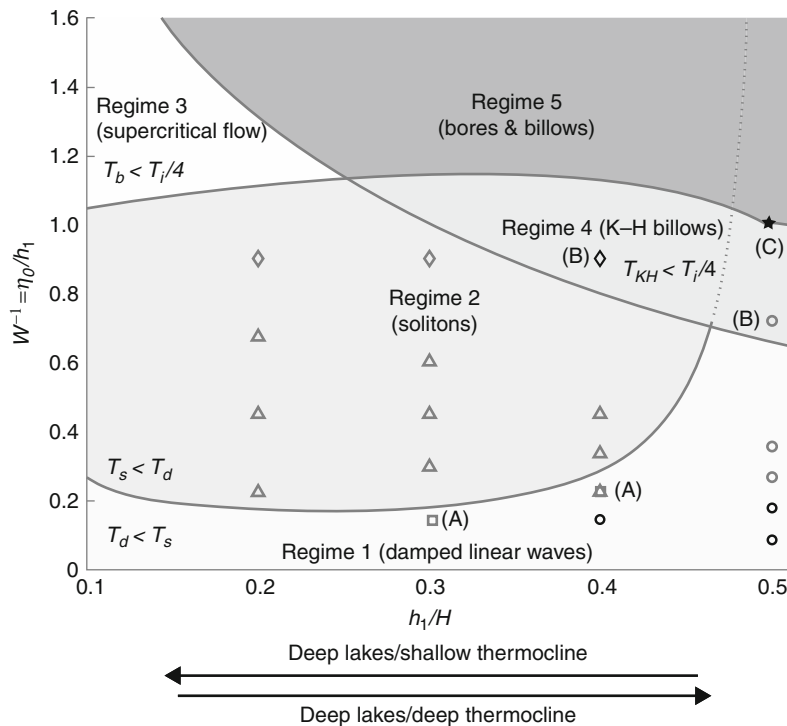
because the no-flux boundary condition causes the inertial circles flatten, becoming shore parallel. Poincaré waves, and the associated currents are, therefore, predominantly found within the basin interior and are best identified in the field by computing rotary spectra of the current and looking for a peak $< T_i$ in the clockwise spectra only.

BSIW damping processes

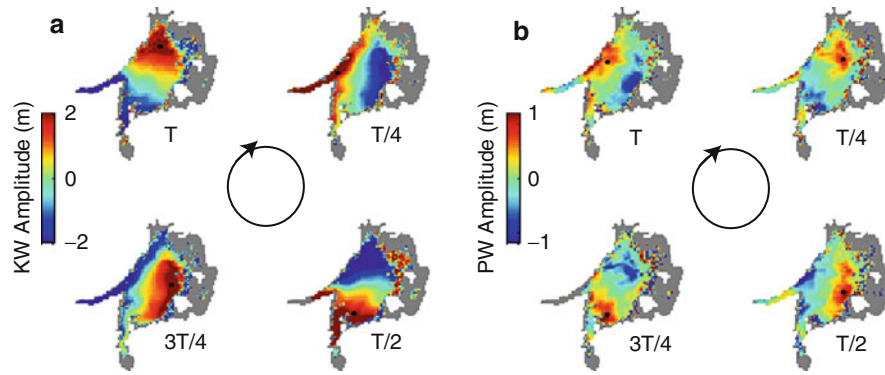
BSIW energy is ultimately damped by dissipation (friction) and the work required by diapycnal mixing (See *Mixing in Lakes*). The processes responsible for dissipation and mixing can be linked to external driving factors, such as wind, stratification, and basin shape, which energize the waves, using the dimensionless Wedderburn number, W .

The magnitude of the wind-induced thermocline setup can be quantified according to $W = \frac{h_1}{\eta_0}$, which is the ratio of the restoring baroclinic pressure force (i.e., gravitational force acting on the tilted thermocline) to the applied wind force. The Wedderburn number is commonly expressed in inverse form $W^{-1} = \frac{\eta_0}{h_1}$ so as to capture the increased tilt of the thermocline with increasing wind stress.

In the case of linear BSIWs, $W^{-1} < \sim 0.3$ (Figure 3), 90% of the wave energy is dissipated by friction as the seiche-induced currents oscillate along the bottom boundary (Imberger, 1998; Wüest et al., 2000) (Figure 2). These currents generate a turbulent bottom boundary layer and shear instabilities (e.g., Kelvin-Helmholtz billows)



Basin-Scale Internal Waves, Figure 3 Damping regimes as a function of W^{-1} and the ratio h_1/H . (Reprinted from Horn et al., 2001.).



Basin-Scale Internal Waves, Figure 4 Evolution of the 15°C isotherm, representing the thermocline displacement in Lake Simcoe from a three-dimensional hydrodynamic simulation (ELCOM). (a) Data have been band pass filtered around the 95-h Kelvin wave period. Each image is offset by a quarter of Kelvin wave period (~ 24 h) and shows the counterclockwise evolution of the wave. (b) Data have been band pass filtered around the 14-h Poincaré wave period. Each image is offset by a quarter of Poincaré wave period (~ 3.5 h) and shows the clockwise evolution of the wave. The *black dot* in each panel highlights the rotation of the wave crest, and the *black circle* represents the time evolution (D. Bouffard, and L. Boegman, unpublished).

form where the thermocline oscillates in a swash zone along the lake bed. During summer, the boundary layer is the primary source of turbulent mixing in hypolimnion and across the thermocline, thus strongly influencing biogeochemistry (Wüest et al., 2000). For $\sim 0.3 < W^{-1} < \sim 1.0$ (Figure 3), the BSIWs begin to lose energy to smaller-scale nonlinear internal waves, e.g., solitary waves (Boegman et al., 2005), which propagate with little energy loss until they shoal and break on sloping topography at the depth of the thermocline, leading to localized dissipation, mixing, and sediment resuspension. Under conditions of strong force and weak stratification, $W^{-1} > \sim 1.0$, BSIWs will degenerate through the formation of internal hydraulic jumps (MacIntyre et al., 2009) and/or shear instability in metalimnion of the basin interior where the Richardson number, $Ri = N^2 / (du/dz)^2 < 1/4$. The instabilities generate mixing in the thermocline region, locally entraining fluid from the epilimnion and hypolimnion causing the remaining 10% of BSIW energy dissipation. Detailed quantifications of the energy flux paths in lakes can be found in (Imberger, 1998; Wüest et al., 2000; Boegman et al., 2005).

Case study: Lake Simcoe

To illustrate the practical use of these equations, we apply them to Lake Simcoe (Canada). During summer, the lake is characterized by $h_1 = 13$ m, $h_2 = 15$ m, $T_1 = 16$ C, and $T_2 = 8$ C (Figure 1). Due to the presence of the long narrow and deep Kempenfelt Bay in the western part of the lake (Figure 4), there are two characteristic lengthscales. The longitudinal scale, which includes the bay $L = 40$ km, while the main basin is $L = 20$ km and $B = 13$ km wide (elliptical shape, with $r = 0.65$). In the non-rotational case, the phase speed of the vertical mode-one seiche is $C = 0.25 \text{ ms}^{-1}$, and the period of the first horizontal longitudinal mode is $T_l = 2 \times 40 \text{ km} / 0.25 \text{ ms}^{-1} = 89$ h. Located at mid-latitude (44°N), $R_o = C/f = (0.25 \text{ ms}^{-1}) / (9.6 \times 10^{-5} \text{ s}^{-1}) \sim 2.6$ km and $S = R_o/R \sim 0.26$ (for the main basin, using

$R = L/2 = 10$ km) indicate that BSIWs will be affected by rotation. The longitudinal internal seiche becomes a Kelvin wave with period $T_l = 89$ h, and the transverse seiche, a Poincaré wave. Estimated for the main basin only, the period of the Poincaré wave is $T_{PW} \sim 16$ h for a rectangular basin (with $r = 0.65$ and $T_l \sim 2 \times 20 \text{ km} / 0.25 \text{ ms}^{-1} = 44$ h) but can be best estimated as an elliptical basin where $T_{PW} \sim 13.7$ h ($T_l/T_{PW} = 1 + 0.09S + 4.67S^2 - 0.346S^3$; see Antenucci and Imberger, 2001; their Table 1, with ratio 2:3).

The calculated wave periods are in good agreement with the observed 95-h and 14-h periods in Lake Simcoe (Figure 1), allowing the observed waves to be identified as Kelvin and Poincaré waves, respectively. Figure 4 shows the evolution of these waves over a wave period and highlights, in particular, the spatial and temporal variability associated with the BSIW – a nearshore Kelvin wave and a more offshore Poincaré wave. Given the circular nature of the lake, the waves shown are mode-one in the radial and azimuthal coordinate directions; higher horizontal modes in these directions are also possible (see Antenucci and Imberger, 2001; Wake et al., 2004).

Summary

Basin-scale internal waves are characterized by the basin shape, stratification, and the influence of the Earth's rotation. When the Burger number is large, $S > 1$, rotational effects are not important and the wind stress generates longitudinal and transverse internal seiches, as $S < 1$. These waves are gradually modified into Kelvin waves, traveling cyclonically with periods much longer than the inertial period, and Poincaré waves, traveling anticyclonically with periods close to, but lower than, the inertial period. In large lakes, $S \sim 0.01$ and the Kelvin wave becomes coastally trapped, while the Poincaré wave is confined to the basin interior.

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Cross-references

[Internal seiches](#)
[Mixing in Lakes](#)
[Stratification in Lakes](#)

BATHYMETRICAL SURVEY OF THE SCOTTISH FRESHWATER LOCHS, 1897–1909

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Introduction

The *Bathymetrical Survey of the Scottish Fresh-Water Lochs* was carried out during the years 1897–1909 under the direction of Sir John Murray and, in the main, Lawrence Pullar. The six volume compilation (Murray and Pullar, 1910), comprising a grand total of 562 loch (lake) bathymetric maps, together with extensive

supporting biological, chemical, geological and physical information, represents an outstanding record of one of the most remarkable feats of field-based scientific endeavor of the late nineteenth and early twentieth centuries. No other country can boast such an important limnological archive; it remains today without equal and has renewed significance thanks to the requirements of the European Union (EU) Water Framework Directive (2000).

Canadian-born Murray (1841–1914), of Scottish parents, was educated at Stirling High School and the University of Edinburgh. He rose to fame as a pioneering oceanographer and marine biologist who played a pivotal role as assistant leader of the *Challenger* Expedition, which explored the deep oceans of the world from 1872 to 1876. He was subsequently responsible for editing and publishing over 50 volumes of expedition reports and was duly knighted in 1898. He returned to Scotland in the 1880s with the intention of undertaking nearshore oceanographic investigations around the coast. With the financial support of his good friend Lawrence Pullar, of Bridge of Allan, Stirlingshire, Murray built the 30 ton steam yacht *Medusa*, which from 1884 until 1891 was employed in the exploration of the nearshore waters around Scotland, including the deep glacially scoured sea lochs of the west coast (Duck, 1990). At this time, it became evident to Murray that virtually nothing was known of the depths of the innumerable fresh-water lochs of the country that formed such a significant scenic legacy of Pleistocene glaciation, especially in the Highlands. Naval officers had, in the interests of navigation, surveyed Lochs Lomond and Awe around 1860, and Murray himself had made a series of depth soundings along the long axis of the lochs connected to create the Caledonian Canal. However, this, along with some soundings in Lochs Katrine, Lomond, and Tay (Buchan, 1871), was the total knowledge of the bathymetry of the Scottish fresh-water lochs at that period.

Murray saw this as a huge gap in knowledge and proposed a systematic survey of the depths of Scotland's fresh-water lochs which he believed would, “in all likelihood result in many new additions to natural knowledge, and would be especially important for comparisons with results in other departments of scientific endeavour” (Murray, 1910). Many parties were interested in the depths of loch basins, such as geologists, in connection with their mode of formation (e.g., Wilson, 1888), fishermen and water supply engineers (Loch Katrine, for example, had become the principal water supply for the City of Glasgow in 1859). On Murray's initiation, the proposal was brought before the Councils of the Royal Societies of Edinburgh and London, both of which were in strong support and, in consequence, urged the British Government of the day in 1883 and 1884 to finance the surveys “in the interest of scientific progress” (Murray, 1910). Treasury support was not, however, forthcoming largely because of a lack of responsibility for inland bodies of standing water: the Scottish fresh-water lochs fell neither under the remit of the Admiralty, whose work was confined to the interests

of navigation, nor the Ordnance Survey, whose mapping operations were confined to dry land.

The Murray and Frederick Pullar Surveys

It is credit to Murray's determination and belief in the scientific merit of such a systematic survey that the idea was not allowed to die in 1884. However, it appears to have lain dormant for several years until it was reinvigorated with the keen enthusiasm of Frederick Pattison Pullar, son of Murray's good friend and benefactor Lawrence. Together Murray and Pullar, the younger, undertook to embark on bathymetric surveys at their own expense, thus commencing an operation that was initially regarded as a "holiday task" in 1897. By that year, however, knowledge of the depths of Scotland's fresh-water lochs had increased somewhat as, in the interim, four bathymetric surveys had been carried out by and officer of the Geological Survey of Scotland, J. S. Grant Wilson. In connection with his studies of the glaciation of the County of Perthshire, Wilson (1888) undertook soundings of the four so-called chief Perthshire lochs, namely, in order of decreasing surface area, Lochs Tay, Rannoch, Earn, and Tummel, for which he recorded maximum depths of 510, 420, 268, and 124 feet, respectively (c. 155, 128, 82, and 38 m, respectively). The results of this pioneering work, incorporating a small, colored, contoured bathymetric map of each water body, were published in the *Scottish Geographical Magazine* (Wilson, 1888). Little is known of Wilson's survey methods or the equipment he used, other than he took a series of depth soundings 50–80 yards apart (c. 46–73 m) along parallel traverses, from one side of a loch to the other (these are all relatively long, narrow, glacially scoured, rock basin lochs), spaced at intervals of about a quarter of a mile (c. 0.4 km). It is presumed that he must have used some form of weighted line; a steam-powered launch was employed to survey the largest body, Loch Tay, while for the other lochs, a rowing boat proved adequate.

Murray and Frederick Pullar commenced their formidable undertaking close to their Stirlingshire homes choosing to survey lochs in the drainage basin of the River Forth, in particular those of the Trossachs and Callander area of the southern Grampian Highlands. Three years later, by 1900, they had completed surveys of eight water bodies, Lochs Katrine, Arklet, Achray, Vennacher, Drunkie, Lubnaig, Voil and Doine for which colored, contoured charts were initially published in the *Scottish Geographical Magazine* (Murray and Pullar, 1900). One year later, in 1901, bathymetric charts of the remaining four major lochs of the Forth basin, Chon, Ard, Leven, and the Lake of Mentieth (Scotland's sole "lake"), together with two lochs of the neighboring Tay drainage basin, Ericht and Garry, were published in the same journal (Murray and Pullar, 1901a, b).

Prior to beginning their surveys proper, Murray and Frederick Pullar made many trial attempts to measure water depths using various devices. As none had proved entirely satisfactory, Pullar, who was of an inventive

nature (Chumley, 1901), designed and built what was subsequently to become known as the "F.P. Pullar Sounding Machine." This was mounted on the gunwale of a boat and comprised a drum around which was wound galvanized steel wire, which passed around a measuring pulley to a tubular weight. The system was such that for every foot (c. 0.3 m) of wire that ran out, the measuring pulley made one complete turn. The motion of the pulley was transmitted mechanically to a series of dials that indicated the length (in feet) of wire paid out in the water column. This ingenious piece of equipment was so successful and reliable that it was employed in all surveys except those in small, poorly accessible hill lochs in which graduated hand lines were used (Murray, 1910).

By the beginning of 1901, Murray and Frederick Pullar had completed a total of 14 loch surveys, and their target of countrywide coverage must have seemed long distant or even unattainable. In February of that year, tragedy struck; on the 15th of the month, Pullar lost his life at the age of 25. Along with many others, he was skating on Airthrey Loch, close to his Bridge of Allan home, when the ice cover gave way. Pullar helped three people to the shore but heroically drowned while trying to rescue a young woman who was suffering from exhaustion in the water. Onlookers claimed that, "he might easily have saved himself had he relinquished his burden: this he refused to do" (Murray, 1910). Murray, who had been out of the country for some months on a round-the-world voyage, arrived back in Britain to learn of his young friend's death the previous day (Chumley, 1901).

This tragedy brought the loch surveys to an immediate halt. Indeed, Murray (1910) wrote that it was his intention to abandon the project altogether. However, Murray's old friend Lawrence Pullar, Frederick's father, was convinced as to the scientific merit of the work and insisted that the surveys should continue as a memorial to his son. To expedite this, he generously donated £10,000 into a trust fund to provide the means to continue the project and took over his son's role as co-director. Such a sum would be equivalent to c. £850,000 today (2007).

The Murray and Lawrence Pullar Surveys

Now placed on a secure financial foundation, the loch surveys recommenced in the spring of 1902, a year after Frederick Pullar's death. The generous funding enabled the employment of a large team of scientific and technical personnel; 48 individuals took part, for longer or shorter periods, including biologists, geologists, physicists, zoologists, surveyors, boatmen and cartographers, as well as numerous boatmen and assistants employed temporarily in different parts of the country. By 1909, when the field operations were drawn to a close, an enormous total of 562 water bodies had been surveyed. "All lochs were surveyed," wrote Murray (1910), "on which boats could be found at the time the work was being carried out." This impressive total comprised not only the major, well-known, "iconic" Scottish lochs (such as Loch Ness and Loch Lomond) but also numerous smaller and less

familiar water bodies throughout the country, including several man-made water supply reservoirs (such as those of the Lomond Hills group, Fife), and many complex, shallow lochs in Shetland, Orkney and the Western Isles. In all, the surveyors recorded over 60,000 point “soundings” of water depth.

When measuring water depth, it is important that the position of the boat is established with accuracy. The Murray and Pullar surveys preceded the use of precision position fixing by techniques taken for granted today (e.g., GPS); they were conducted along traverses between known end points, typically prominent shoreline features such as deltas at the mouths of influent streams or buildings that provided a clear line of sight. Uniform spacing of soundings was accomplished by recording the water depth as quickly as possible so as to avoid boat drift after a fixed number of strokes (typically 10, 15, 20, or 50 according to the length of traverse) by the oarsman. In order to keep the boat on course when running lines of soundings, an aligning mirror was often used in the survey boat. By this means, an onshore feature behind the surveyor could be kept in line with a feature in front on the opposite bank.

During the period of the loch surveys, measurements of water temperature, movements (surface and internal seiches) and chemistry, loch biology and the character of the bottom sediments were also carried out. The bathymetric maps themselves are masterpieces of cartography, prepared and color lithographed by J. G. Bartholomew & Son of Edinburgh at a scale of 3 in. to 1 mile (1: 21,120). The depth soundings were contoured at regular intervals, each division being colored in a shade of blue, becoming progressively darker with increasing depth. Around half of the 233 plates that comprise the 562 individual maps also show the topography shaded with darkening shades of brown indicating progressively higher relief. The later maps in the series (those of Murray and Pullar, 1910, Vols. 5 and 6) show only the blue colorations of water depth. The maps, together with a descriptive account of each loch, chapters on the associated scientific observations and tables of statistics relating to the suite of water bodies (length, surface area, maximum depth, mean depth, volume; the interrelationships between which have been evaluated by Gorham, 1958), were collated into six volumes and published by the Challenger Office, Edinburgh (Murray and Pullar, 1910). At the time the six volume set, representing around 12 years of fieldwork, retailed at five guineas (£5.5 s.d = £5.25p). Today, the maps have been made available free of charge on the Internet by the National Library of Scotland (<http://www.nls.uk/maps/early/bathymetric/>).

The deepest sounding measured in all of the c. 60,000 of the 562 surveys was of 1, 017 ft (309.98 m) in Loch Morar. The second deepest was found to be Loch Ness (maximum 754 ft, 229.82 m), followed by Loch Lomond (632 ft, 192.63 m), Loch Lochy (531 ft, 161.85 m), Loch Eriach (512 ft, 156.06 m), Loch Tay (508 ft, 154.84 m),

Loch Katrine (495 ft, 150.88 m) and Loch Rannoch (440 ft, 134.11 m). In his introduction to the six volumes, Murray (1910) reflected that, “It was rather amusing at times to observe the result of the soundings on the inhabitants of districts in which the lochs are situated. As a rule, lochs, or some parts of a loch, are regarded as very deep or without bottom. When a loch with this reputation was found to be relatively shallow, the result would be questioned, and a feeling of affront or injury prevailed among the inhabitants of the district.”

Significance of the “Murray and Pullar” Surveys Today

In the intervening century since the “Murray and Pullar” surveys were completed, the character of Scotland’s lochs has changed considerably, not least in the Highlands. The advent of hydroelectric power generation following World War II has resulted in the construction of large numbers of mass concrete, buttress and arch dams. In some valleys, these have created new lochs (e.g., Loch Faskally, Loch Errochty), whereas at other sites, dams have raised the water levels, and thereby the surface areas, of existing lochs (e.g., Loch Tummel, Loch Garry). Natural sediment influx and, in places, increased rates associated with land use changes have continued to contribute to delta growth at the mouths of influent rivers and streams and to offshore loch floor deposition. The Murray and Pullar surveys thus represent important baselines from which to evaluate such changes in hydromorphology a century or so later.

Where re-surveys of water bodies have been undertaken with modern methods of sounding and position fixing (e.g., Duck and McManus, 1985; Duck, 1986; Lowe et al., 1991a, b; Young and Shine, 1993) and the bathymetric data can be directly compared with those of Murray and Pullar, the differences serve to emphasize the accuracy of the latter. While modern methods may reveal deeper hollows that the original surveyors missed using point soundings, the overall morphology of the basins was accurately captured using what today are regarded as relatively primitive surveying techniques.

In recent years, the Murray and Pullar surveys have assumed an even greater significance due to The EU Water Framework Directive (WFD), which was introduced in 2000 to establish a new legal framework for the protection, improvement and sustainable use of all water bodies, including lakes, across the European Union. The Directive stipulates that surface water bodies, such as lakes, should achieve good ecological and chemical status by 2015. Implementation of the WFD presents a series of challenges to EU member states, one of which concerns the lack of adequate baseline data, such as lake bathymetry. For example, Great Britain (England, Wales and Scotland) has over 40,000 lakes >1 ha in surface area (and thus covered by the WFD), but bathymetric data are available for less than 2% (Rowan et al., 2006). Morphometric data, for example lake volume, derived from bathymetric surveys, are necessary for the calculation of important parameters such as basin residence time. The requirement for

good quality bathymetric data is essential for lake management and for the effective compliance of the WFD. When such data are not available, it is necessary to make estimates based on empirically derived relationships from map-derived parameters and predictive models that derive from actual bathymetric data (Rowan et al., 2006). The 562 Murray and Pullar surveys from Scotland, even though they actually cover only a small fraction of the lochs in the country, represent over 90% of the currently available bathymetric data for lakes in Great Britain. They are thus of prime importance as input data to such predictive models, that vary according to lake typology, and collectively place Scotland at an advantage for WFD implementation in terms of the quality and quantity of its baseline lake bathymetric data.

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BEAVER DAMS AND PONDS

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Introduction

Like the human being, the Canadian beaver is the only animal creating its own habitat by modifying the biophysical environment. The result of this modification is the creation of a lake environment along streams or ditches. Beaver is sometimes named “the engineer of Nature”. Its name seems to come from the Sanskrit word *kasturi*, which means *musk*, because the castoreum used in perfumery is known by Indo-Europeans since antiquity (Anonymous, 2006).

Beavers distribution

Three species of beaver exist. The first one, the Mountain beaver (*Aplodontia rufa*), is living in the Rockies along the Pacific coast of North America, from California (USA) to southern British Columbia (Canada) (Banfield, 1974). The second one, the European beaver (*Castor fiber* L.), was living on almost all the European territory before the XVIIth century. Now, it is mainly living in Russia, Scandinavia, Bielorussia, and Baltic countries. But it is scattered in other European countries except Italy, Iberian Peninsula, south of Balkan Peninsula, and Caucasus where it is absent (Manet and Fichet, 2004). The last one, the Canadian (or American) beaver (*Castor canadensis* Kuhl), is living on almost all the territory of Canada and USA as far as the northern limit of trees (Banfield, 1974). The Canadian beaver has been introduced in Finland in 1937, Tierra del Fuego (Chile) in 1948, USSR in 1950, and France in 1970 (Prescott and Richard, 1996).

Beaver characteristics and habits

The Mountain beaver has not the anatomic characteristics of the Canadian beaver and then is not a true beaver. It is a rodent that must be compared to a muskrat without a tail and living in burrows along streams. The Mountain beaver sometimes builds little dams with vegetation debris and mud (Banfield, 1974).

The European beaver has the anatomic characteristics of the Canadian beaver but weighs less than 30 kg. It has no interest in dam construction and confines its efforts in digging burrows into the stream banks (Prescott and Richard, 1996).

The Canadian beaver is the biggest rodent of North America and the second biggest that exists in the World. The biggest is capybara of South America (*Hydrochaeris hydrochaeris*). The Canadian beaver may weigh up to 35 kg (Banfield, 1974) or even 45 kg (Prescott and Richard, 1996). Its large webbed back feet serve as oars and its flat tail is covered with scales and serves as a rudder when swimming, as a support when cutting off

trees, and as a lever, but not as a trowel. Beaver has long and sharp incisors serving to cut trees as large as 40 cm. Beaver has more ability in swimming than in walking. The yearly average beaver litter is two young, living with their parents for 2 years. Afterward, the young beavers are driven out of the colony by their parents and have to create new colonies. It is the female that selects the site of the colony. As the beaver does not hibernate, it must constitute a viable and safe environment for the winter time.

Construction of the habitat

When a beaver colony is settling, beavers begin by erecting a watertight dam across a small stream or ditch. They choose a site with a soft substrate and in an environment where there are enough deciduous trees for at least a year (Banfield, 1974). Beavers usually settle down along a stream of low flow without important fluctuations, with a longitudinal slope of less than 3–6% and a watershed of less than 15 km² (Comeau, 2006). The dam is made of poles, branches, roots, pieces of rocks, turfs, and mud (Figure 1). The dam is anchored in the substrate with poles and branches set up parallel to the current and with the tips oriented upstream. Other materials are placed across and tamped by water flow. The dam is widened and heightened by piling successive layers of sticks and debris. As the water level rises, beavers lengthen the dam at both ends. The dam must be high enough to create a pond of about 2–3 m deep to allow the beavers to swim under an ice cover that can reach a thickness of about 1 m. The overflow is always located in the central part of the water bed where the flow is the highest. The dams can reach a height and a thickness at the base of 2–3 m and a length varying between a few meters to about 200 m. Mills (1913) reports a 650-m-long dam in Montana. Beavers can also build secondary upstream dams to protect stockpiles of food (food caches) and downstream dams to help in sustaining the main dam by creating a water counterpressure



Beaver Dams and Ponds, Figure 1 Beaver dam on Anticosti Island (Québec, Canada). (Photo: Dubois, J. -M. n° 82-5-26.)

at its base. The flooding of the forested land causes the death of numerous trees on a surface larger than the pond itself.

The dam protects the lodge built by the beavers with the same materials as the dam. The lodge is located at the center or on the side of the pond. The lodge is round, conical, and usually measures between 2 and 3 m high and between 3.5 and 7 m in diameter (Figure 2). The accesses are submerged to baffle the predators, and ramps give access to the emerged inner chamber. The beaver gets its materials by cutting trees and can even build small channels to float the logs toward the pond. The dam maintains a constant water level to protect the lodge and to get access to the food.

The main source of food is the cambium of deciduous trees, including leaves, buds, and twigs. The main species are Trembling aspen (*Populus tremuloides*) Willows (*Salix* sp.), Alder (*Alnus* sp.), White Birch (*Betula papyrifera*), Mountain-ash (*Sorbus* sp.), Cherry tree (*Prunus* sp.), and Maple (*Acer* sp.). Sometimes, mainly in northern regions, beavers also eat the cambium of



Beaver Dams and Ponds, Figure 2 Beaver lodge in a pond center in Rivière-des-Mille-Îles Park (Laval, Québec, Canada). (Photo: Leblond, M., Parc de la Rivière-des-Mille-Îles, *Le Monde en images*, Collège de Maisonneuve, Montréal, n 15226: <http://www.ccdmd.qc.ca/>)

coniferous trees. An additional source of food is aquatic plants and rhizomes. The pond allows the growth of a diversity of such plants and increases their biomass. The beaver maintains one or several underwater stockpiles of food nearby its lodge for winter time. A wood supply is always necessary to repair the dam and the lodge. When that wood supply is worn out after 2 or 3 years, the colony moves to another site. Some colonies, mainly in Europe, do not build lodges but live in burrows into the stream banks with underwater accesses. There are 2–14 members for each colony with an average of 4. Beavers stay close to the stream banks and their area of cutting down trees. The width of these areas can reach 150 m.

The surface of the ponds (lakelet) can be as little as few tens of square meters but can sometimes reach 1 square kilometer. A survey by airphoto interpretation with terrain validation in the Kouchibouguac Canada National Park in New Brunswick shows that beavers have inundated a surface of about 3 km² of the 293 km² of the park surface (Figure 3). The 138 beaver colonies within the limits of the park have built 152 ponds with a mean surface of 2 ha (Dubois et al., 1997). Some colonies have built as much as six dams of 0.5–1.5 m high and of 4–200 m length. Some ponds had a surface as little as 0.03 ha while others could reach over 30 ha (Boucher et al., 1997). All the colonies were not active because 35% had no evidences of beaver activities. These evidences have been recognized and summarized by several research projects (Dubois, 1982; Labrie and Dubois, 1988; Labrie et al., 1992; Dubois et al., 1997; Boucher et al., 1997): high water level pond, well-maintained dam and lodge (conical shape) indicated by fresh mud, fallen trees close to the banks of the pond or the stream, floating channel that may reach several tens of meters in length, and underwater stockpiles of food (only in autumn).

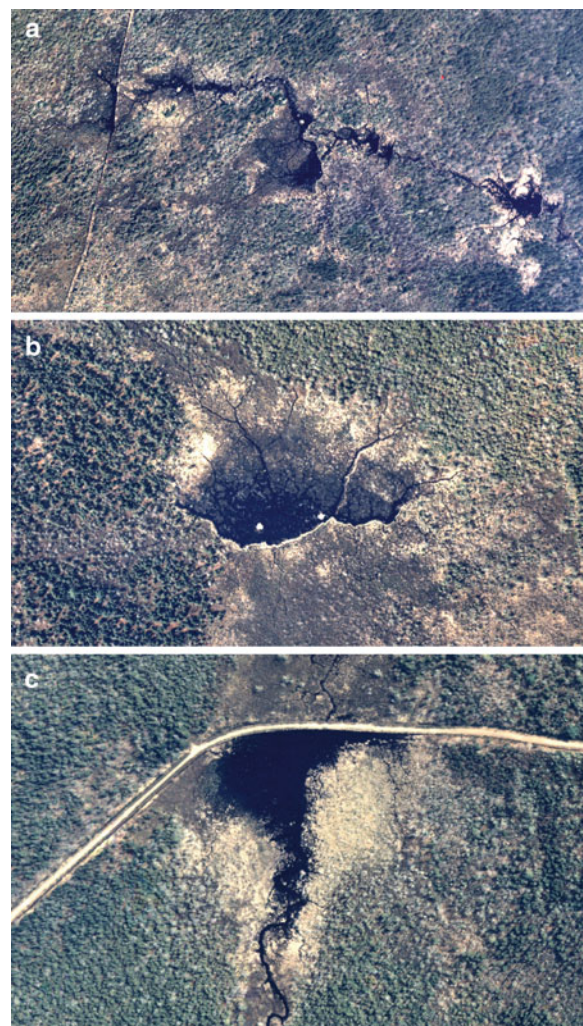
Impacts on the environment

The first impact related to beaver activities is the modification of a part of a watercourse into a lake environment. Trees, bushes, and grass of the inundated areas rapidly die, but tree stumps can stand up for many decades. This terrestrial vegetation is rapidly replaced by aquatic vegetation. In drained out ponds abandoned by beavers, the regeneration of the trees can take as much time.

Ponds have also an impact on the fluvial dynamics. Ponds give rise to the deposition of sediments due to the reduction of the water speed flow entering the pond. The importance in the deposition of sediments in the ponds is correlated to the quantity of sediments carried out by the fluvial system and the duration of the pond. In some extreme situations, the watercourse can change place when a breach opens into one of the lateral parts of the dam.

Dams have an impact on the stream fish habitat. They hold up the fish circulation and cause the rise of the water temperature which can be prejudicial for some salmonids.

Beavers also have an impact on the human being infrastructures. They can obstruct channels or culverts flooding



Beaver Dams and Ponds, Figure 3 Beaver pond landscapes in Kouchibouguac Canada National Park: (a) chain of ponds on a little stream; (b) big pond with a long dam built by the beavers; (c) big pond dammed by a road dike after the obstruction of a culvert by beavers. (Photos: Government of Canada n A31533-49 and 173.)

roads, railroads, seasonal recreation places, cultivated lands, and valuable woodlands. On Anticosti Island in the northern part of the St. Lawrence Gulf (Québec), beavers have been seen constructing a dam obstructing ditches on both sides of a road and the road itself, thus flooding the road on several 100 m. In all these situations, beavers must be captured and relocated in places similar to the original site (Dubois et al., 1997).

On the other hand, beaver ponds can have a positive effect. Indeed they help to reduce the spring flood peak discharge of watercourses reducing the erosion risks. They also create an aquatic habitat similar to a freshwater swamp, which attracts a diversified fauna of fishes, waterfowl, amphibians, reptiles, and small and great mammals.

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BENGAL BASIN, SEDIMENT SINK

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Introduction

The Bengal Basin is one of the most extensive sediment reservoirs in the world and constitutes the lower flood-plain and delta plain deposits of India and Bangladesh, at the mouth of the Ganga–Brahmaputra–Meghna River systems. The delta formation initiated at ~11 ka when the sea level rose to trap the riverine, fluvio-deltaic to overlying estuarine and mangrove-mud-containing shells;

wood; and organic debris (Umitsu, 1993; Goodbred, 2003). The most notable sediment discharge took place during ~11–7 ka when the sediment flux in the Ganga–Brahmaputra delta was at least 2.3 times higher than the present. The Ganga–Brahmaputra River systems together carry the world's largest sediment load, 80% of which is delivered during the four monsoon months (Goodbred and Kuehl, 2000). As a consequence, the Bengal Basin acts as a huge sediment sink with wide dispersal systems often related to a wide range of climate change.

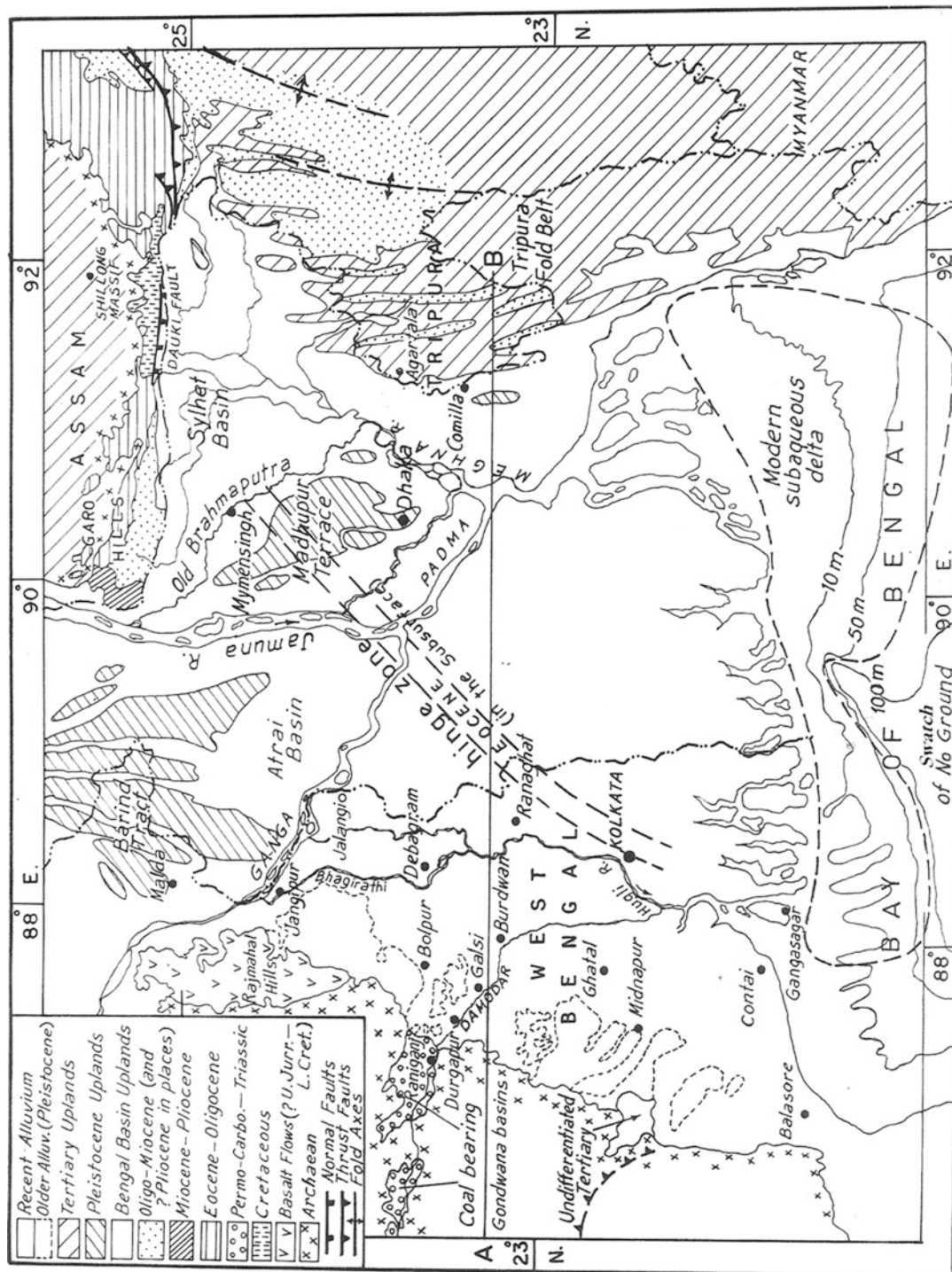
Goodbred (2003) suggested that the deposits of Bengal Basin have responded to multi-millennial scale climate change all through the time of their deposition across the huge basin. Chauhan et al. (2004) have identified between 11 ka and 9.5 ka, two major phases of fluvial influx in the Bengal Basin. Lithostratigraphic and geochronologic studies from bore-hole samples have established the Late Quaternary (the latest Pleistocene and Holocene) succession of the Bengal Basin consisting mainly of sand, silt, and clay with a few distinctive beds useful for correlating stratigraphic units (Banerjee and Sen, 1987; Hait et al., 1996; Goodbred and Kuehl, 2000). There has been variation in physical and chemical weathering processes in the sedimentary sequences with change in climatic condition. The Late Quaternary sediments of Bengal Basin have shown high concentration of smectite and kaolinite during ~10–7 ka, indicating enhanced chemical weathering under warmer and more humid conditions (Heroy et al., 2003).

Bengal basin boundary

Bengal Basin (lat 21° N to 26° N and long 87° E to 92° E) is the foreland basin of the Eastern Himalayan Range. The basinal area occupies the subaerial and subaqueous deltaic deposits of the Ganga–Brahmaputra Rivers covering parts of northeast India and almost the whole of Bangladesh. The north and northeast boundaries of the basin are delineated by the east–west extending Shillong Massif separated by the Dauki Fault. The eastern side of the basin is bounded by the north–south extending uplifted fold belt, the Tripura Fold Belt (i.e., the Indo-Burma collision boundary). The northwestern boundary of the basin is delineated by the basaltic traps of Rajmahal Hills. Further south–southwest of the basic trap deposits lies the gneissic complex of the Archean Shield. The acidic Archean rocks disappear below the veneer of the older and recent alluvium between lat 87° E and 88° E. Patches of coal-bearing Gondwana sedimentaries and undifferentiated Tertiary rocks unconformably overlie the Archean gneissic terrain at the contact of the Pleistocene and recent alluvium (Figure 1).

Tectonic setting

The Bengal Basin is tectonically active in both space and time and is tectonically highly disturbed by earthquakes, folding, faulting, and other neotectonic movements. All these have direct impact in controlling the geomorphic



Bengal Basin, Sediment Sink, Figure 1 Geological map of the Bengal Basin.

and sedimentary features like the patterns of river courses, shifting and avulsion of rivers, sedimentary facies, and sediment dispersal patterns. The basin margin in the west is marked by a number of subsurface ridges and depressions followed by a series of en echelon faults further east. The stable shelf of the basin in the west very gently dips to the southeast to attain its maximum depth in Bangladesh. The basin bottom deepens with the Archean basement complex overlain by the basaltic flows. The edge of the shelf is characterized by a northeast–southwest trending subsurface “hinge zone” – a zone of subsurface flexure (Figure 1) on the overlying Eocene limestone horizon. The flexure has been recorded at a depth of about 4,725 m below Kolkata and has been supposed to be responsible for the tectonic movement at the shelf–slope break. The regional southerly slope of the Bengal Basin along with eastward migration of the Ganga over the Holocene also owes its origin, at least partly, to the movement on the hinge zone. An increasing rate of southerly tilt of the Indian part of the basin is also noticed due to relatively greater rate of subsidence of the southwestern part of the hinge through the Tertiary and Recent times (Sengupta, 1972).

The northern part of the Bay of Bengal constitutes the southern limit of the Bengal Basin. The basin has been gradually closing because of the oblique eastward subduction beneath the Tripura Fold Belt (Indo-Burman Range) and the Sunda Outer Arc. These plate-driven tectonic processes have been responsible in generating the subsidence rate of the basin up to 4 mm/year (Goodbred and Kuehl, 2000). The compressional stress from the north causing upliftments in various parts of the basin comes from the overthrust block of the Shillong Massif. The eastern part of the Bengal Basin is tectonically more complex compared to the southern part where the delta front is less active tectonically. The 1782 earthquake caused avulsion of the course of the old Brahmaputra River. The uplifts and subsidence at several places altered the accommodation space, rate of sediment delivery, river channel widening and constrictions, and sediment dispersal.

Vertical displacement of sedimentary sequences is evidenced from a number of places in the basin. The Madhupur Terrace and the Barrind Tract are uplifted (>10 m) alluvium deposits of Pleistocene age (Morgan and McIntire, 1959). The eastern part of the basin as far as the Madhupur Terrace is affected by the shortening of the accretionary wedge of the Tripura Fold Belt (Indo-Burman Fold Belt). The Madhupur Terrace is located in the SSW of Shillong Massif, whereas the Barind Tract is in its northeast. Evidence of Holocene neotectonic upliftments (5–10 m) is noticed from three areas within the basin. These include (1) Mymensigh Terrace situated along the course of the old Brahmaputra River in the north of the Madhupur Terrace, (2) the Komilla Terrace in the east of the basin in the contact of the Tripura Fold Belt, and (3) around Kolkata (Samad and Khandoker, 1984). Many of the tectonic movements, imprints of which were recorded from sediment accumulation history in the

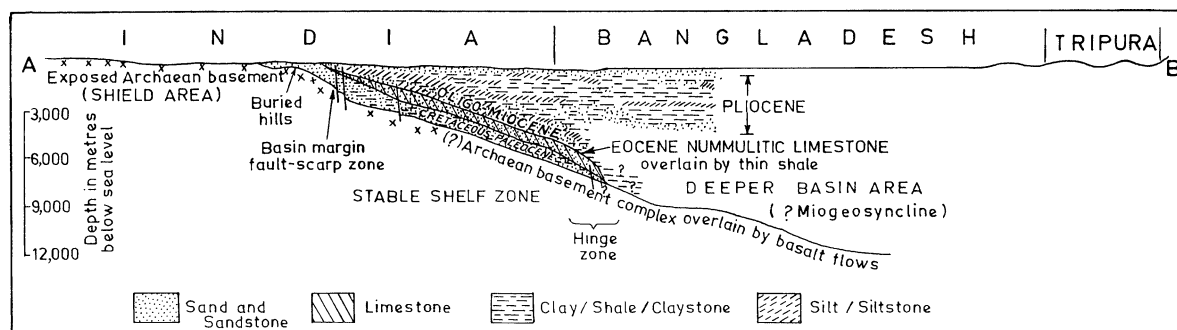
basin, were influenced by isostatic loading, subsidence, overthrust, and compressional forces.

In contrast to the areas of upliftments, there are two peludal sub-basins (<3 m deep) within the Bengal Basin. These are the Sylhet Basin in the south of the Shillong Massif and the Atrai Basin in the south of the Barind Tract (Figure 1). The Sylhet Basin, a foreland trough, is formed due to overthrusting of the Shillong Massif (Alam, 1996; Goodbred and Kuehl, 1999). The subsidence rate in the basin has been determined to vary from 1 to 3 mm/year. Differential rates of compaction of sediments and/or tectonically induced subsidence characterize these intrabasinal areas.

Bengal basin as a sink of sedimentation

The Bengal Basin has captured the Ganga–Brahmaputra River systems at their downstream stretches. The two rivers have coalesced in the Bengal Basin about 150 km upstream of the present land–sea interface. The combined sediment load of the two rivers to the tune of 10^9 t/year had led the basin to be identified as one of the world’s largest depocenters. The Bengal Basin is comprised of about 100,000 km² of lowland floodplain and delta plain areas. The Ganga alone discharges 520×10^6 t of annual sediment load, 95% of which is delivered during the four wet monsoon months (June–September) of the year (Goodbred, 2003). From north to south, the Ganga–Brahmaputra delta has two portions, a subaerial delta and a subaqueous delta. The subaerial delta has an upper river floodplain followed southward by the deltaic plain with many distinctively different geomorphic zones like the Sundarban mangrove swamps, estuaries, intertidal mudflats, and beach-ridge complex. The high-resolution seismic studies have definitely established the Holocene evolution of the subaqueous counterpart with a typical clinoform structure (Kuehl et al., 1997). This subaqueous delta started to form on the Bengal shelf since about 7,000 years B.P. with a sediment fill rate of 0.42×10^9 t/year and yielding a fill volume of $1,970 \times 10^9$ m³ (Kuehl et al., 1997). Estimation of this volume has revealed that the subaerial delta holds 30%, and the subaqueous delta holds 40% of the Holocene sediment load of the rivers; the remaining 30% is supposed to reach the submarine canyon “Swath of No Ground” and the deep sea Bengal fan. The growth of the subaqueous delta with active accumulation of sediments in the clinoform morphology also explains the apparent insignificant progradation of the present-day shoreline (Coleman, 1969). Although the Bengal Basin is the primary sink of sediments of the Ganga–Brahmaputra Rivers, the deep sea Bengal fan also serves as the ultimate sink for these Himalayan Rivers (Curry and Moore, 1971; Bhattacharya, 1999).

The depositional history of the Bengal Basin initiated with the deposition of the clastic rocks of Cretaceous–Palaeocene age (Figure 2). Thin lenticular shale/claystone units were deposited on the southeasterly sloping Archean basement complex with basaltic traps. These rock units



Bengal Basin, Sediment Sink, Figure 2 Cross section across the Bengal Basin to show subsurface configuration in Lithofacies (After Sengupta, 1972).

were overlain by the Eocene Nummulitic Limestone over the same southeasterly sloping underlying units on the western part of the Bengal Basin margin of West Bengal (India). The overlying thick Oligo-Miocene to Pliocene clay/claystone and sand/sandstone units constitute the bulk of the early-phase deposition of the Bengal Basin that reaches up to a depth of over 14,000 m in Bangladesh. The latest Pleistocene and Holocene sedimentation in the Bengal Basin had been divided into five units by Umitsu (1993). The lowest unit is characterized by gravels and formed at the maximum epoch of the last glacial ice age when level in this area increased rapidly. The immediately overlying unit is made of sand and gravel of age 12,000 year B.P. The middle unit is sandy and is formed during Middle Holocene when the coastline retreated southward, whereas the upper two units are made of sand, silt, and clay with intercalated peats at places. The uppermost Late Holocene transgressive unit is chiefly composed of silt and clay with intercalated peat layers. The radiocarbon-dated cores taken at places helped subsurface mapping and delineation of Holocene deltaic sequences and underlying transgressive units of Late Pleistocene alluvial deposits of the Bengal Basin, particularly in the western part (Stanley and Hait, 2000). The vast portion of the modern top stratum tidal deposits with various sub-environments in the Bengal Basin is characterized by numerous tidal and wave-generated bedforms and biogenic structures (Bhattacharya, 1999, 2001). There has been an interfingering of fluvial, fluvio-tidal, and tidal sedimentary facies in the basin across shoreline from the landward to the seaward direction.

Present status

Being positioned at the mouths of Ganga, Brahmaputra, and Meghna Rivers along the northern boundary of the Bay of Bengal, the subaerial part of Bengal Basin is a “bread basket” for a high-density population of India and Bangladesh. In addition to the natural forcing imparted by periodic cyclones and wave surges, anthropogenic stresses causing influx of organic and inorganic pollutants in the sediments have become a matter of great concern for the last few decades (Chatterjee et al., 2007;

Binelli et al., 2007). Recent estimate reveals that out of over 235 million population in the Bengal Basin and its adjacent areas, about 80 million people are facing a serious environmental stress from the toxic poisoning of arsenic in ground water. Both the natural setting and anthropogenic activities are supposed to be responsible for the arsenic toxicity (Acharyya et al., 2000).

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BROWNIFICATION OF LAKES

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Synonyms

Browning

Definition

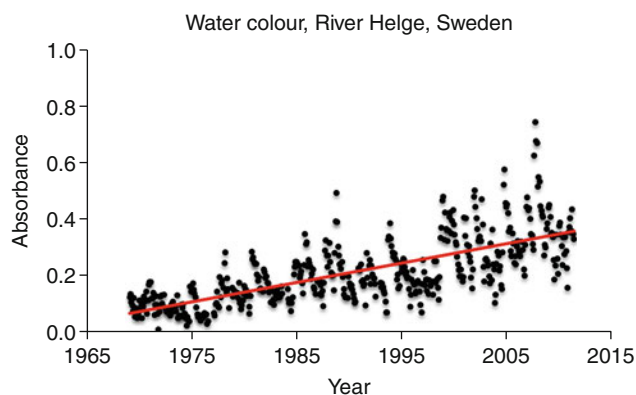
Brownification signifies an increase in the yellow-brown color of lake and stream water, caused mainly by dissolved humic matter of terrestrial and wetland origin, which absorbs solar radiation strongly in the short wavelength part of the visible spectrum.

Long-term changes in water color - causes and consequences

Many streams and lakes, from temperate to tropical climate zones, contain high concentrations of dissolved organic matter (DOM). There are two main sources of DOM in inland waters: internal production via plankton and aquatic macrophytes, and external inputs of DOM of terrestrial or wetland origin. Terrestrially derived DOM often dominates in freshwaters, and if concentrations are high (e.g., DOC – dissolved organic carbon – above 10 ppm in a nutrient-poor lake), the water is usually visibly brown-colored (Figure 1). Lakes with brown-colored water are called dystrophic or polyhumic. Terrestrial and wetland DOM is composed largely of high molecular weight residues (humic matter) of microbially processed plant detritus, leached from the soil profile. The (humic) color of water has traditionally been measured using a platinum salt solution as reference, thus lake color is given as mg Pt/l. This color scale has today been substituted by measurements of absorbance, at wavelengths around 400 nm. The DOM concentration and color of lake and stream water show both seasonal and year-to-year fluctuations, as well as long-term trends (Pace and Cole, 2002). Over the last decades, there has been a marked “brownification” (or browning (Roulet and Moore, 2006)) of a large number of running waters and lakes in NW Europe and in N America (Forsberg, 1992; Hongve et al., 2004; Evans et al., 2005; Roulet and Moore, 2006; Vuorenmaa et al., 2006). Color has in several cases more than doubled in a few decades (Figure 2). DOC has also increased, although often not as much as color. Brownification may thus be caused both by changes in the quantity and in the quality of terrestrially derived DOM. An increase in the iron content of surface water may also cause brownification. Brownification has been attributed to decreased



Brownification of Lakes, Figure 1 Brown-colored lake, the province of Småland, south Sweden. Photo W. Graneli 2007.



Brownification of Lakes, Figure 2 Color (as absorbance at 420 nm of filtered water) of River Helge at Lake Hammar, Scania, south Sweden. Data from national monitoring (<http://webstar.vatten.slu.se/db.html>).

atmospheric sulfur deposition (reversed acidification, Monteith et al., 2007), climate change, e.g., increased precipitation/runoff (Hongve et al., 2004; Erlandsson et al., 2008) and higher temperatures (Weyhenmeyer and Karlsson, 2009) and changes in land use, as well as combinations of these. Although most of the proposed potential drivers of brownification are connected to human influences, natural fluctuations, especially in climate, could also be involved. If brownification is an effect of wetter and warmer conditions and/or changes in land use (reduced cultivated area, more coniferous forests), a continued brownification could be expected in coming decades. However, if climate change causes reduced precipitation and run-off, lakes may on the contrary become less colored. If reversed acidification, due to greatly reduced emissions of acidifying sulfur oxides since the 1970s is the cause, brownification is a return to pre-acidification conditions, and the process will level off. Paleolimnological evidence suggest that lakes in south Sweden were as brown as today or even browner 100 years ago, supporting the reversed acidification hypothesis (Cunningham et al., 2011). Monitoring data and experimental acidification of soils also support this hypothesis (Monteith et al., 2007; Ekström et al., 2011). Brown coloring DOM has profound effects on lake ecosystems, organism communities, and on human use of lakes and lake water. Brownification affects lake ecosystems by drastically reducing the penetration of solar radiation into the water column, which causes a decrease in lake ecosystem primary production, as well as secondary production, e.g., of benthic invertebrates and fish (Karlsson et al., 2009). On the other hand, brownification increases organic carbon available for bacterial growth, intensifying oxygen consumption and CO₂ production. Although there are some positive effects, e.g., increased UV-protection of organisms, brownification has mostly negative consequences from a human perspective. Among these can be

mentioned: more costly treatment procedures for drinking water, reduced aesthetic value for water sports, reduced biodiversity, and reduced fish production (Karlsson et al., 2009). Lakes and streams are globally significant conduits for the transfer of CO₂ to the atmosphere (Tranvik et al., 2009), and brownification will cause increased CO₂ emissions to the atmosphere from freshwater ecosystems (net heterotrophy), due to intensified microbial processing of DOM in lakes and running waters.

Summary

Brownification is the process whereby the brown color of stream and lake water increases. Brown color of freshwater is caused by strong absorption of short wavelength visible solar radiation by dissolved organic matter, possibly in combination with iron, leached from soils in the catchment. Brownification is probably an effect from greatly reduced anthropogenic sulfur emissions during the last 30–40 years, increasing soil and surface water pH and mobilizing DOM bound to the soil under more acid conditions. However, there is no consensus among scientists with respect to the driver(s) behind brownification. There are also alternative or complementary explanations: climate change (especially increased precipitation and temperature) and land-use changes. Paleolimnological studies indicate that lakes in southern Sweden were even browner 100 years ago compared to today. Brownification has mainly negative effects on human use of freshwaters.

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Cross-references

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C

CARBON CYCLE IN LAKES

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Introduction

The lacustrine carbon cycle involves the interactions of gaseous, dissolved, and solid forms of C. Inputs include carbon derived from the atmosphere, surface water, groundwater, regolith, and bedrock. Transformations within the lake system include biotic and abiotic processes occurring in both the presence and absence of oxygen. Losses occur to the atmosphere, to streams and groundwater, and to the sediment underlying the water (Figure 1). Many lacustrine processes have familiar counterparts in marine systems. Lakes are not small oceans however; important aspects of the carbon cycle such as the relationship between dissolved gases and the atmosphere, and the role of organisms in carbonate mineral formation, differ strikingly in lakes as compared with the ocean. Lakes are strongly influenced by processes occurring in their catchments, because of the high ratio of shoreline to open water, while the oceans are affected only locally by continental processes. Large lakes such as the Laurentian and East African Great Lakes behave more like oceans than like small lakes; however, their water chemistries differ significantly from typical ocean chemistry and from one another. Lakes process a tremendous amount of carbon, given their small collective areal extent, sequestering organic and inorganic carbon in their sediments as well as emitting large quantities of carbon dioxide and methane to the atmosphere.

Density stratification of lakes plays a major role in carbon cycling. The differentiation of the cold, dark,

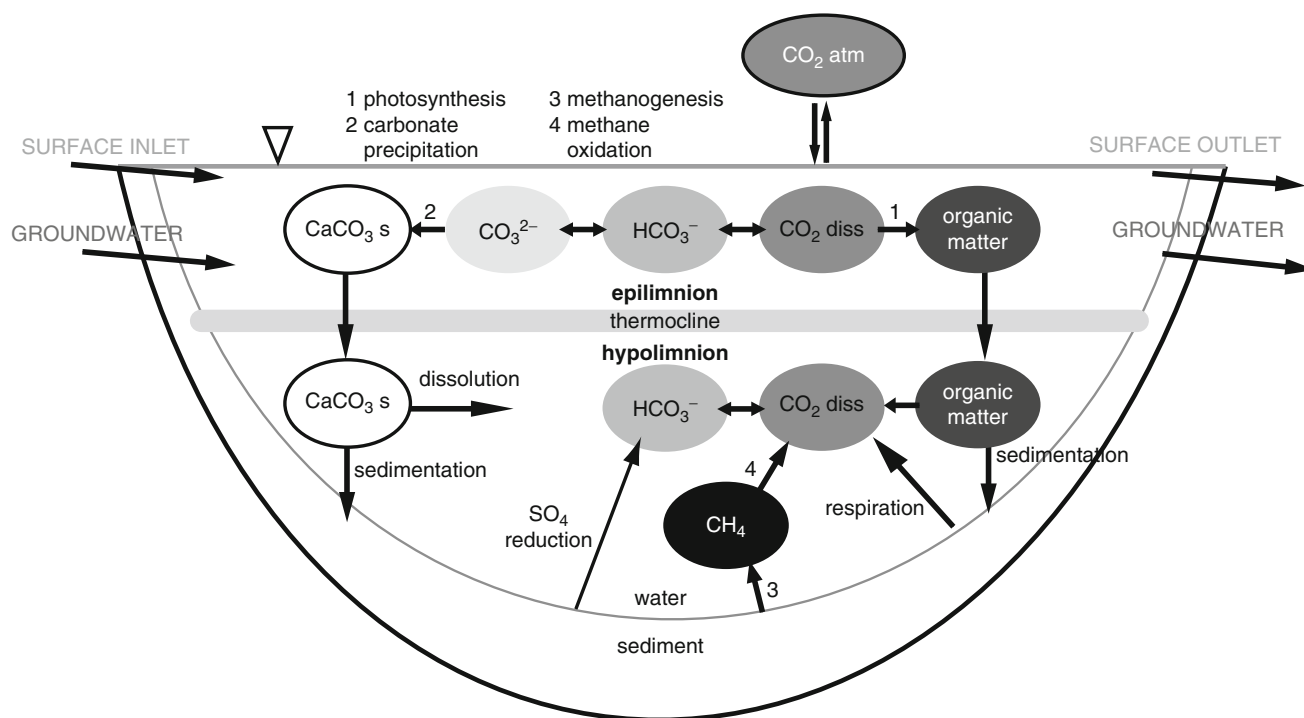
stagnant hypolimnion from the warmer mixed epilimnion, part or all of which may be within the photic zone, promotes different biological and chemical processes in the two layers. Photosynthesis, wind mixing, and atmospheric exchange lead to higher pH and dissolved oxygen saturation (or supersaturation) in the epilimnion, while the hypolimnion, isolated from the atmosphere and receiving sinking organic matter, may evolve toward anoxia, carbon dioxide supersaturation, and low pH due to respiration.

Lake water chemistry is highly variable, ranging from almost pure rainwater in lakes with small catchments on crystalline bedrock, to several times the salinity of seawater, and from low to high pH (~3–11). The ionic composition of lake water is a reflection of the surrounding geology and is further affected by climatic factors such as precipitation-evaporation balance. Major ions in surface water may include virtually any combination of K^+ , Na^+ , Mg^{2+} , Ca^{2+} , HCO_3^- , CO_3^{2-} , SO_4^{2-} , Cl^- ; under reducing conditions in anoxic bottom waters, dissolved Fe^{2+} and Mn^{2+} may also be major. Lakes with sufficient alkalinity may precipitate carbonate minerals, similar to the formation of limestone in the oceans; these are sometimes termed “hardwater” lakes, and in these lakes carbonate geochemistry represents an important part of the C cycle.

C reservoirs and fluxes in lakes

Lakes and the atmosphere

Lake surface waters are typically out of equilibrium with respect to atmospheric carbon dioxide (Cole et al., 1994). This finding might be expected for periods of the summer when high rates of algal photosynthesis draw down dissolved CO_2 below atmospheric equilibrium values; however, many lakes surveyed are actually well above CO_2 saturation. Supersaturation occurs because of the influence of the catchment on lake water chemistry.



Carbon Cycle in Lakes, Figure 1 Schematic diagram of the major carbon cycle processes in hardwater (carbonate mineral producing) lakes. Softwater lakes with lower pH and DIC (see text) lack the carbonate ion and carbonate mineral (CaCO_3 s) portions of the cycle but are otherwise comparable. DOC is excluded from the diagram for simplicity; it acts as an organic matter source for a number of microbial and abiotic processes.

Particulate and dissolved C-bearing materials enter the lake via surface and groundwater and overland flow, and are processed (decomposed, dissolved, etc.) there, releasing CO_2 into the lake water. The diffusion of gases across the air-water interface is relatively slow, allowing the lake water to exceed CO_2 saturation. Evasion of CO_2 and of methane (see below) to the atmosphere can occur both by diffusion and by ebullition (bubbling out).

Dissolved inorganic carbon and the carbonate system

Dissolved carbon dioxide is hydrated to the uncharged species $\text{H}_2\text{CO}_3^\circ$ (carbonic acid), which rapidly dissociates into HCO_3^- (bicarbonate ion), CO_3^{2-} (carbonate ion), and protons. The relative abundance of these dissolved species (when including dissolved CO_2 and $\text{H}_2\text{CO}_3^\circ$, collectively termed “dissolved inorganic carbon,” DIC, or “total inorganic carbon,” TIC) depends on the pH of the water, with $\text{H}_2\text{CO}_3^\circ = \text{HCO}_3^{2-}$ (and CO_3 negligible) at pH=6.35 and $\text{HCO}_3 = \text{CO}_3^{2-}$ (and H_2CO_3 negligible) at pH=10.33. Some algae and higher plants can use HCO_3^- as well as CO_2 in photosynthesis. Carbonate ion reacts with a cation such as Ca^{2+} or (less commonly) Mg^{2+} , Na^+ , Fe^{2+} , or Mn^{2+} to form carbonate minerals such as calcite (CaCO_3). Calcite often precipitates abruptly and massively in events known as *whittings* (e.g., Hodell et al., 1998). These events, as well as more steady carbonate

precipitation, are triggered by a combination of factors that increase calcite saturation and all occur during early to mid-summer: rising water temperature (carbonate solubility decreases with increasing temperature), photosynthetic drawdown of CO_2 (increasing pH and driving the carbonate equilibria toward CO_3^{2-}), and evaporation (increasing the concentration of Ca^{2+} and CO_3^{2-}). Algae in the water column also act as nucleation points for the precipitation of minerals and generate aqueous microenvironments far exceeding carbonate saturation. With the exception of the green alga *Phacotus*, which forms a calcite lorica, and pelagic ostracodes, which have calcified valves, all carbonate minerals formed in the pelagic zone of lakes are abiogenic (though biologically mediated; Kelts, 1978). Lacustrine carbonate minerals thus stand in sharp contrast to those found in oceans, where virtually all carbonate occurs as the tests of organisms such as foraminifera and coccolithophorids. The shells of ostracodes and molluscs can be important components of the littoral sediment in lakes as well.

Dissolved organic carbon

Myriad biogeochemically important but poorly characterized molecules comprise the suite of compounds known collectively as dissolved organic carbon (DOC). DOC is divided into classes based on chemical separation techniques or molecular masses. While some DOC molecules

are recalcitrant (and thus persisting in aquatic environments without further decomposition), some DOC compounds that are stable in soils or groundwater may be subject to photolysis when they enter the light environment of lakes, and can also be utilized by aquatic microbes. Respired DOC is thus a significant contributor to the CO₂ supersaturation of lakes described above (e.g., Cole et al., 2002). DOC may be a relatively small fraction of the lacustrine carbon pool in hardwater systems, but is by far the largest pool in some softwater lakes.

Photosynthesis and respiration

Green algae (chlorophytes) and diatoms (bacillariophytes) are ubiquitous photosynthetic organisms in pelagic zone in lakes. They convert CO₂ (and in some cases HCO₃⁻, as noted above) into biomass. Their relative abundance is affected by windiness (diatoms' silica frustules are denser than water and so they require turbulent water to stay in the photic zone), nutrient abundance (N, P, Si, and others; most lakes are considered to be P-limited), and turbidity. In some lakes, especially those with high dissolved P levels, these algae may be replaced in middle or late summer, when dissolved N is depleted, by cyanobacteria (blue-green algae) that can fix nitrogen from the atmosphere and thus can capitalize on the remaining available P. Some cyanophytes are responsible for nuisance toxic algal blooms. In the littoral zone, submerged, floating-leaf, and emergent plants draw CO₂ (or HCO₃⁻) from the water or CO₂ from the atmosphere. Most of these are higher (vascular) plants, but multicellular charophyte algae and aquatic mosses (bryophytes) are also common, as are epiphytic diatoms living on the surface of the substrate or on plants. Some taxa of charophytes that live in hard water deposit a carbonate mineral coating on their surfaces.

After these plants die, their remains sink toward the lake bottom. A large percentage of particulate organic matter is grazed by zooplankton or respired under oxic conditions. Respiration releases CO₂ back into the lake water, and hypolimnetic CO₂ saturation can be orders of magnitude above atmospheric equilibrium. The remaining organic matter, along with precipitated carbonate minerals and detritus washed into the lake, accumulates on the lake floor. Diagenetic (postdepositional) alteration of this material can occur under oxic or anoxic conditions. Which conditions prevail at the sediment-water interface and in the lowest part of the water column depends upon the flux of organic matter (and other reduced materials) relative to the concentration of oxygen in the bottom waters and its rate of resupply. Lake sediments are almost always anoxic due to the relatively high organic carbon content (a few percent to over 40%) and the slow diffusion rate of oxygen through overlying and pore water. The oxic-anoxic transition, then, typically occurs around the sediment-water interface, and in some lakes with high sediment oxygen demand, higher in the water column. This hypolimnetic oxygen depletion may be seasonal (e.g., occurring only under summer stratification or under winter ice cover),

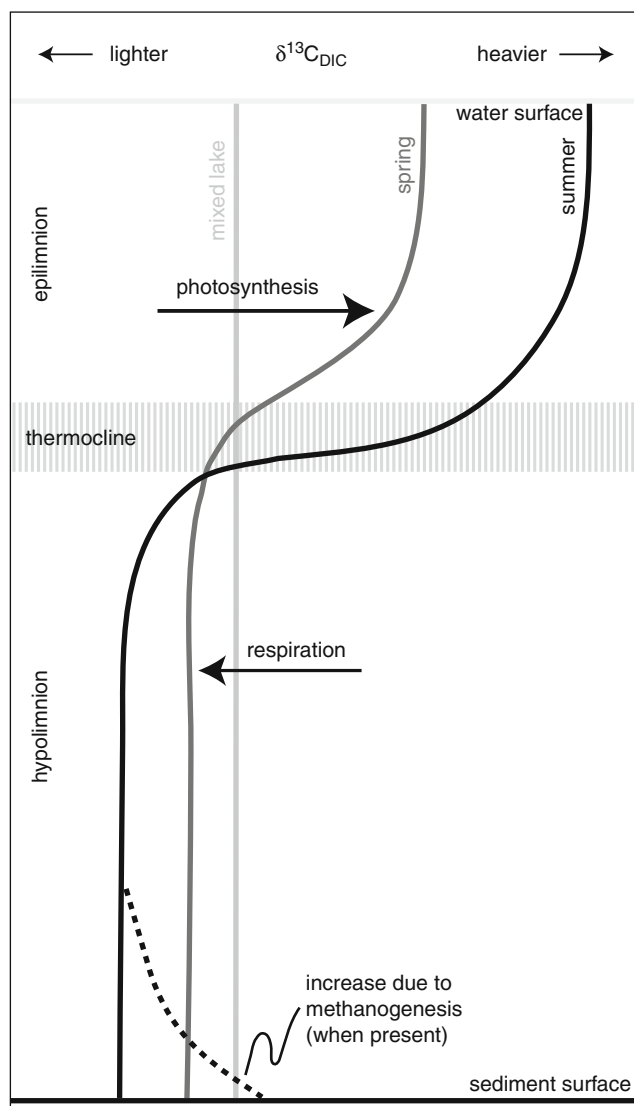
or it may be persistent or permanent if the water column remains unmixed. Under anoxic conditions, methane-producing bacteria (methanogens) in the sediment or water column reduce dissolved CO₂ or ferment organic molecules and release CH₄. Dissolved methane may diffuse through the water column, and be consumed by methanotrophic bacteria at the oxic-anoxic transition, or it may come out of solution and bubble out of the lake water to the atmosphere (e.g., Walter et al., 2006). Carbonate minerals may partially or fully dissolve while sinking in the water column, or in the sediments, because the release of CO₂ by respiration lowers pH and increases carbonate solubility (e.g., Dean, 1999).

Carbon isotopes

Photosynthesis and respiration exert the main controls on the carbon stable isotopic composition of DIC. In surface waters, photosynthesis preferentially takes up ¹²C into organic matter, leaving the DIC pool enriched in ¹³C ("heavy"). Respiration of this "light" sinking organic matter releases ¹³C-depleted DIC into the bottom waters, causing the hypolimnetic DIC pool to become lighter (Hollander and McKenzie, 1991). A typical profile of δ¹³C of DIC in a lake is shown in Figure 2. In some lake systems, microbial processing of organic matter in anoxic bottom waters exerts some influence on δ¹³C of DIC (Myrbo and Shapley 2006): in lakes with relatively high sulfate, dissimilatory sulfate reduction using an organic molecule as an electron donor generates HCO₃⁻ with a δ¹³C reflecting the relatively light organic matter source. In contrast, methanogenesis generates very ¹³C-depleted CH₄ and leaves the DIC pool ¹³C-enriched or heavy. Carbonate minerals in the catchment and dissolved carbonate in groundwater and surface water also contribute to the δ¹³C of lake water. These sources are typically isotopically heavy if the C is derived from carbonate minerals, and light if derived from oxidation of organic matter. Because of these inputs, in-lake processing, and disequilibrium with atmospheric CO₂, lake surface δ¹³C values are not readily predicted. Similarly, the radiocarbon (¹⁴C) content of surface water DIC is not typically in equilibrium with atmospheric values, and thus radiocarbon dating of aquatic organic matter (i.e., material whose carbon source was DIC rather than atmospheric CO₂) usually provides a date that is "too old" relative to the date the organism actually died.

Carbon accumulation and the sedimentary record of lakes

Particulate carbon accumulates in lake sediments as carbonate minerals (usually calcite) and a variety of organic remains representing the organisms that lived in and around the lake. These two components together can comprise nearly 100% of the sediment in some lakes, though diatoms and detrital mineral debris usually occur in significant percentages as well. Organic remains are dominated by algal and higher-plant debris, including both altered (charcoal, carbonized soil organic matter) and unaltered



Carbon Cycle in Lakes, Figure 2 Generalized profile of the carbon stable isotopic value of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) in a lake over the period from holomixis through summer stratification. Photosynthesis drives values more positive, or “heavier,” while respiration drives values more negative, or “lighter.” In lakes with significant methanogenesis in the sediments, a positive shift is seen in values near the sediment surface.

tissues, with a smaller contribution from invertebrates such as insects, cladocerans, ostracodes, etc. Vertebrates are extremely rarely represented, although fish remains (teeth and sometimes scales) do occur.

Small lakes typically have higher sedimentation rates than larger lakes, due to their high shoreline-to-open-water ratio, which leads to both more direct particulate input of surficial material and usually more input of nutrients and other dissolved species, potentially supporting higher productivity and more mineral precipitation, respectively. Pelagic sedimentation rates in large,

oligotrophic lakes may be on the same order as those of the ocean, at <0.02 cm/year (in terms of linear accumulation rate) or <0.01 kg/m²/year (mass accumulation rate; these figures are examples and not necessarily related to one another). In small lakes, especially in urban and agricultural regions, rates can exceed 1 cm/year or 5 kg/m²/year (e.g., Engstrom et al., 2007). Littoral zones experience both deposition and erosion, and thus are difficult to compare with the profundal zone, but sediments tend to be dominated by minerogenic material relative to organic material, due to wave-reworking and removal of low-density organic matter, and decomposition under oxic conditions. Lakes’ relatively organic-rich sediments make them excellent (though relatively small) potential hydrocarbon source rocks (Kelts, 1988). Mesozoic rocks representing lacustrine deposition in former rift basins of coastal Brazil and West Africa, for example, have recently been exploration targets. The small size of most lakes and rapid sedimentation rates mean that most are geologically transient features, lasting perhaps 10,000–100,000 years, although large lakes in tectonically active regions (e.g., modern lakes of the East African Rift, and Eocene lakes of the Green River Formation) can persist for millions of years due to basin subsidence and the resulting increase of accommodation space.

The study of core samples of lake bottom sediments (paleolimnology or limnogeology) can provide a long-term record of environmental changes in and around a lake. Compositional, geochemical, and biological analyses are routinely used to “reconstruct” past climate changes, geological processes, and human impacts. Some records collected extend back more than one million years, and can provide approximately decadal or better resolution of changes in the lake and the surrounding region. Stable isotopes of carbonates and organic matter in the sedimentary record are used as “proxies” for past productivity, organic matter source (e.g., aquatic vs. terrestrial) and water column stratification and circulation.

Acknowledgments

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Cross-references

Estuarine Hydrology
 Light and Primary Production in Lakes
 Nutrient Balance, Light, and Primary Production

CARIBBEAN-CENTRAL AMERICA, LAKES REVIEW

Rhodes W. Fairbridge (Deceased)

Introduction and generalities

The Caribbean Sea is properly an arm of the Atlantic Ocean that is rimmed to the north and east by the West Indies or Caribbean islands, comprising the *Greater Antilles* (Jamaica, Cuba, Hispaniola, and Puerto Rico) and the *Lesser Antilles*, the *Windward Islands*, that is Virgin Is. to Dominica, and the *Leeward Is.*, and the southerly ones, Martinique to the Grenadines and Grenada. Also included in the Leeward Is. are the so-called ABC ones (Aruba, Bonaire, Curaçao). In addition, but separate, are Barbados, Trinidad, and Tobago. Likewise separate and distinctive are the Bahamas, and Turks and Caicos Is.

Central America is taken to embrace the continental area from the Mexican border to northwest Colombia, that is, Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica, and Panama, a total area of 592,017 km² (228,578 square miles). Its highest point is the Tajumulco volcano in Guatemala (4,220 m, 13,845 ft). The region lies entirely in the northern hemisphere, from north of the Tropic of Cancer, about 27°N, to about 7°N, and from 59°W to 92°30'W.

Geologically, the mainland belt represents an elongated isthmus that has fluctuated in height and width since Mesozoic times, but has been severed repeatedly, permitting an intermittent marine link (Tethys) to bring “mediterranean” biota to the western Pacific. Because of tidal

cycles, the marine currents in Tethys were generally east to west. The last interruption was in Pliocene times when land faunas began their exchanges between North and South America and marine endemism began in the eastern Pacific. The principal rock formations are therefore mainly volcanic, of various ages. Exceptionally, in Guatemala, there are fossiliferous marine Permian formations.

During plate tectonic history, the North American and South American plates have jostled repeatedly, as they fractured away from the Eurasian and Gondwana landmasses, the taphrogenesis beginning in late Triassic to early Jurassic times. The main fault systems were strike slips, those in the north being mainly sinistral (SW–NE, E–W, and NW–SE), while those in the south are mainly dextral (NE–SW and E–W).

In the Greater Antilles, the geological record goes back to the Paleozoic, but is nevertheless marked by an alternation of relatively deep-sea marine formations and volcanic intervals. Because of the tropical climates, limestones are particularly prevalent, and today some of the world’s more spectacular karst landscapes are to be found in Cuba and the other islands.

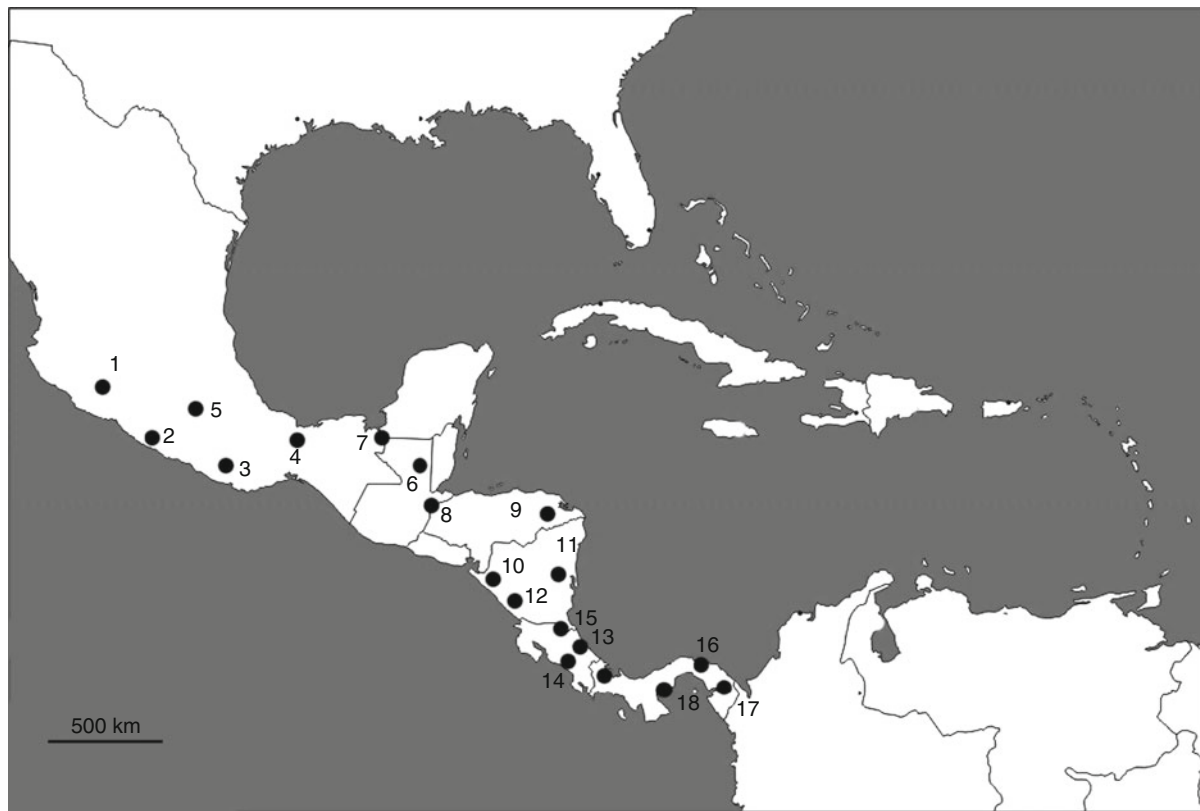
Drowned karst (with its “Blue Holes”) is a feature of the Bahamas.

The Lesser Antilles, in contrast, have long been dominated by a west-dipping subduction zone which results in the twin arcs of islands, a style first recognized in the East Indies (Indonesia). The outer arc (the Atlantic site) is marked by nonvolcanic, mainly limestone islands (Virgin Is., Antigua, and Barbados), while the inner arc (the Caribbean side) is marked by much more numerous volcanoes (St. Kitts, Montserrat, Guadalupe, Dominica, Martinique, St. Lucia, St. Vincent, Grenada, etc.). Related to the outer arc are the limestone banks of the Bahamas, and Turks and Caicos Is., that are ancestrally related to Florida and their ancient Gondwana foundation.

Climatically, the entire area is dominated by the northeast trade-wind system, but is subject to a great deal of orographic modification. Furthermore, there is the diurnal sea-breeze/land-breeze effect. There is little seasonality and practically no continentality. Orographic rains are thus normal in almost every month but heavier in the northern summer. Because of the rain shadow effect, certain areas are semiarid (e.g., northwest Costa Rica; much of Haiti). Tropical cyclones and hurricanes are commonly experienced in the islands but less so on the mainland shores. These occur as a rule in May–June and September–October, starting off the coast of West Africa, gaining strength in the warmer sea-surface temperatures of the Western Atlantic, building over the Caribbean to full-fledged hurricanes, bearing to the right, and impinging on Puerto Rico or Cuba before heading north.

Lake classification

Categories of lakes in this region are few in number compared to the larger continental unities, partly because of their low latitudes and partly because of lack of any



Caribbean-Central America, Lakes Review, Figure 1 Distribution of lakes in Caribbean-Central America. 1, Chapala; 2, Patzcuaro; 3, Texcoco; 4, Catemaco; 5, Cuitzeo; 6, Atitlan; 7, Terminos; 8, Izabal; 9, Cartasco; 10, Managua; 11, Colciboica; 12, Nicaragua; 13, Humedal C. N.; 14, Pyramid; 15, Arenal; 16, Bayano; 17, Irazu; 18, Poas.

endorheic drainage. The important lakes are shown in (Figure 1).

Structural

Structural depressions of complex graben type are present both in the mainland and in the Greater Antilles (Cuba and Hispaniola).

1. *Lake Nicaragua* (4,960 km², 3,100 square miles) is 163 km (102 miles) long and 70 m (230 ft) deep. It is the largest lake in Central America. It is linked to Lake Managua by the Tipitapa R in the north and drained in the southeast by the San Juan R. that debouches into the Caribbean.
2. *Lake Managua* (220 km², 575 square miles) is 61 km (38 miles) long. The capital city of Nicaragua, Managua is situated on the southwest side.
3. *Lago de Izabal*, situated in eastern Guatemala, draining northeast via the Dulce R to the Caribbean, it is controlled by a NE-SW trending graben.
4. *Etang Saumatre*, a swampy salt lake in the southeast part of Haiti, it is about 30 km east of Port-au-Prince.
5. *Lago Enriquillo*, a salt lake, similar to E. Saumatre (Haiti), 45 m (150 ft) below sea level, it is in the southwest part of the Dominican Republic.

6. *Lago Gatun*, situated about 10 km south of Colon, the Atlantic end of the Panama Canal, the Gatun Lake is now connected with the canal and its locks.

7. *Lago Bayano*, 35 km long and situated south of the Cordillera San Blas in eastern Panama, the lake drains into the Gulf of Panama.

Volcanic

Crater lakes are numerous, although generally small. When the volcano is dormant, the lake is generally a picturesque tourist attraction, and sediment coring may provide a useful historical record. However, when the igneous activity is revived, the lake sediments become converted into a boiling mud that is likely to generate a lahar that may have catastrophic impact on the populations of the lower slopes. The waters of crater lakes range from highly acidic (e.g., pH 2.7, L. Alegria) to alkaline (pH 9.9, L. Nejapa).

1. *Lake Arenal*. Located in Costa Rica, the volcano, 1,960 m (6,429 ft) high, erupted last in 1968, but the rift (15 km to northwest) is occupied by a spectacular lake.
2. *L. Irazu*. Also in Costa Rica, near the city of Cartago, the Irazu volcano erupted in 1841, 1910, and 1963. It is said that on a clear day, it is the only place where both

Atlantic and Pacific oceans can be seen at the same time. During the last activity, water-saturated tephra (ash) created a major lahar.

3. *Lago Poás*. Likewise in Costa Rica, 30 km northwest of the city of San José. The volcano is 2,708 m (8,884 ft) high. Pictures of its February 1953 steam eruption in the lake were shown in the Fairbridge (1968) *Encyclopedia of Geomorphology* (p. 220).
4. *Lago Nejapa*. Associated with a line of volcanoes in western Nicaragua, extending northwest from the Lago de Managua, this lake is distinguished for its extreme alkalinity (pH 9).
5. *Laguna de Alegria* on the Tecapo volcano of El Salvador, with four other lakes in this small country. It is notable for the extreme acidity (pH 2.7) of its waters.
6. *Lago de Atitlan*. Situated in a major caldera depression at an elevation of 1,433 m (4,700 ft) in western Guatemala, this lake is about 20 km (12 mi) wide and 300 m (1,000 ft) deep. A youthful volcanic cone 354 m (11,604 ft) high rises south of the lake.

Karst lakes

Extensive areas of limestone terrain associated with karst features are found in Cuba, Hispaniola, and Puerto Rico and in the north part of Guatemala (a karst landscape that extends into southwest Mexico and Yucatan). Sinkholes are commonly associated with small lakes and then known as "cenotes." The latter played an important religious role with the ancient Mayan people.

The karst lakes involved are small and do not constitute major features.

Coastal lagoons

These are scarce on the Pacific coast of Central America, but common on the Atlantic Coast, facing the Caribbean. Here, the coasts are subject to the northeast Trade Winds and periodic hurricanes. From north to south, the principal features are:

1. *Belize coast*. It is largely protected by offshore coral reefs (barrier reefs).
2. *Honduras coast*. A north-facing shore with a number of west-growing sandspits but without forming closed lagoons. The largest example is the *Laguna Caratasca*.
3. *Nicaragua coast*. The "Mosquito Coast" is well-named because it is oriented N-S and is low and swampy, but few lagoons are closed. The largest is the *Laguna de Perlas*.
4. *Costa Rica's Caribbean coast* is similar, and the northwest part is identified as the "Parque Nacional Tortuguero." The southeast contains the site of the "Parque Internacional La Amistad."
5. *Panama Coast*. In the west is the island-studded *Laguna de Chiriquí*. East of Colon are several national parks, but the numerous islets (Archipelago de San Blas) do not form closures.
6. *Cuba Coasts* are marked by numerous archipelagos parallel to the shores, but without closed lagoons, except on the offshore island *Isla de la Juventud* which has several small lakes.
7. *Hispaniola Coasts* lack lagoons except for one northeast of Cabo Beata in southwest Dominican Republic.
8. *Puerto Rico Coasts* lack closed lagoons except for a few small examples on the south coast (e.g., L. Guánica).
9. *Coasts of Jamaica*. Jamaica's north coast is rocky or fringed by coral reefs. However, the south coast is low and swampy with many small lagoons, e.g., Black R. to Parotee Point, Alligator Pond, the Alley to Rocky Pt, Hellshire Hills, and The Salt Ponds (near White Horses) speak for themselves.
10. *Coasts in the Bahamas, and in Turks and Caicos Is.* These islands are, for the most part, associated with bank margins, that is, with deep water on one side and shallow on the other. In consequence, they are, except for *Andros*, mostly long and narrow. A second exception, in the far south, is *Great Inagua* which contains a major enclosure, *Lake Rosa*, 30 km long, and a small one at Matthew Town.
11. *Coasts in the Lesser Antilles*. Most of the islands are volcanic but lacking in lakes, while the remainder are small, limestone features. The latter include the Netherlands Antilles, the "ABC islands" of *Aruba*, *Bonaire*, and *Curaçao*, of which Bonaire includes a lagoon, famous among geologists for its precipitation of dolomite.
12. *Trinidad and Tobago Coasts*. These islands represent geological extensions of the Northern Cordillera of Venezuela, separated from them by the Gulf of Para. Sandspits along the east coasts, e.g., Cocos Bay, do not contain lagoons. On the west side is the Caroli Swamp.

Asphalt lake

On Trinidad a unique product of mud-volcano activity, driven by tectonics and hot waters with petroleum products, is a large tar seepage that has long been known as the Asphalt or Pitch Lake. The asphalt was exploited for many years for sealing boats and for waterproofing the roofs of dwellings. The natural upwelling of the hot water and tar has always replaced the quantities removed from the surface.

Dams and reservoirs

Central America is not featured by any world-class dams and reservoirs, but is distinct for one particular system, the Lago Gatun and the Lago Alajuela which are modified to provide the daily demands for refilling the locks of the Panama Canal.

Climatically favored by the northeast trade winds, most of the continental areas of Central America and both the Greater and Lesser Antilles are well watered, but certain areas are marked by rain shadows and as a result are

semiarid. In those places, the natural vegetation reverts to a cactus scrub, although there are no actual deserts. Normally, the trade-wind clouds are intercepted by the elevations and furnish almost daily precipitation. Some parts of southern Cuba, much of Haiti, and parts of the Dominican Republic are affected by droughts or are generally semiarid.

In Honduras, the *Represa el Cajon* (reservoir) is situated 40 km southeast of San Pedro Sula. There are several in El Salvador and Nicaragua. Numerous small reservoirs occur in Cuba and Puerto Rico.

Cross-references

[Classification of Lakes from Origin Processes](#)

[Coastal Lagoons](#)

[Maracaibo Lake](#)

[Paleolimnology](#)

[South America, Lakes Review](#)

CARINTHIA LAKES AND RESERVOIRS IN AUSTRIA

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Introduction

Carinthia is a southern province of Austria and situated at the border to Italy and Slovenia. There is hardly any alpine region containing so different types of lakes, littoral zones, and various types of landscapes within a similar limited space. Their specific character depends to a minor extend on their surface area but is based predominantly on a till 28°C warm epilimnion and the meromictic mixing of

some of the lakes. There are around 1,270 stagnant water bodies in Carinthia, including some high alpine pools and artificial ponds.

630 of that stagnant water bodies are situated in an altitude above 1,000 m, most of them being rather small with surface areas of less than 0.1 ha. The cumulated surface of all stagnant water bodies in Carinthia covers 60 km², to which the four largest Wörthersee ([Photo 1](#)), Millstätter See, Ossiacher See, and Weissensee ([Photo 2](#)) contribute 50 km² ([Figure 1](#)). In [Table 1](#), all lakes larger than 19 ha are listed. The deepest lake is Millstätter See with 141 m, followed by Weissensee (99 m) and Wörthersee (85 m).

The Carinthian lakes are geological rather young and were formed at the end of the last ice age, when the large glaciers withdrew around 15,000–12,000 years BC. The general shape of the basins was in many cases determined by the tectonic shape of former old valleys. The formation of lakes is based on glacial erosion of the valley floors and the deposition of moraines.

The chemical composition of the water is shown in [Table 2](#).

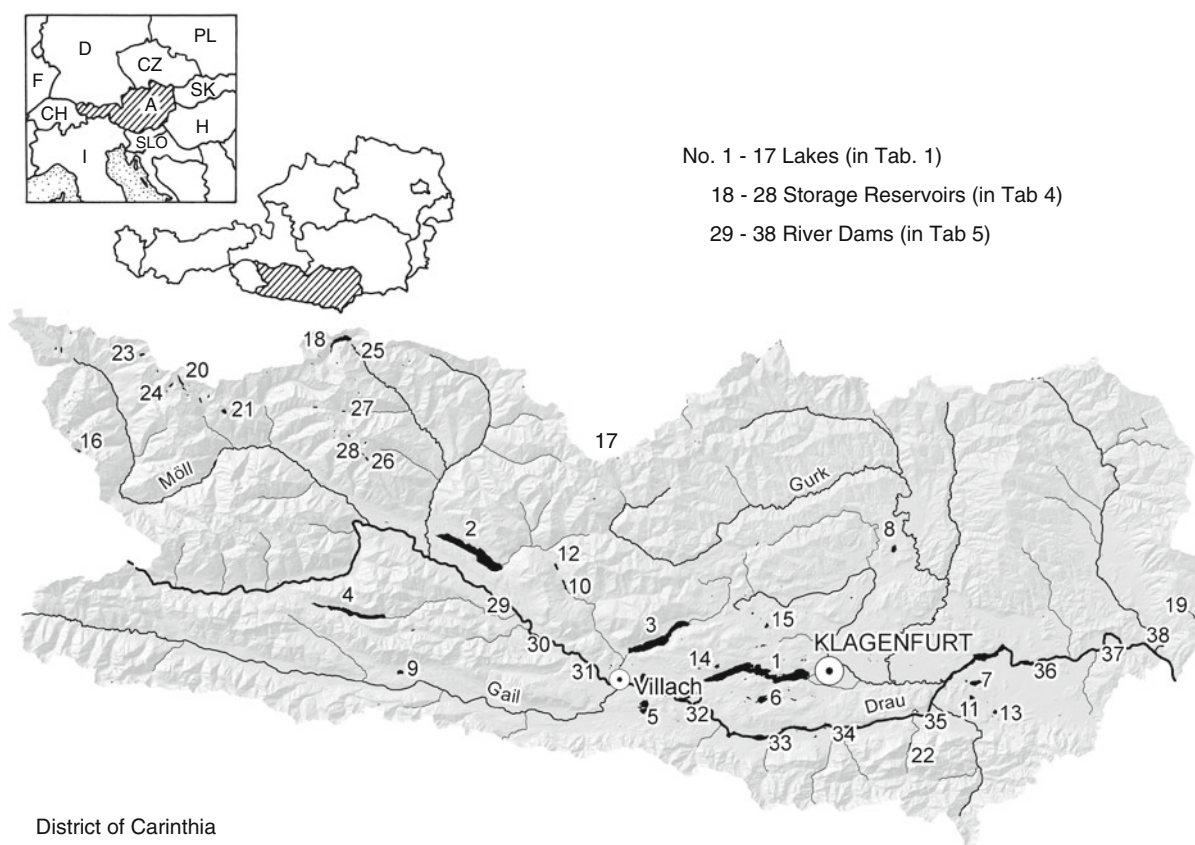
The manifold landscapes around the lakes have inspired nature lovers and artists like Johannes Brahms, Gustav Mahler, and Alban Berg long before the establishment of modern tourism. The settlement of monasteries and convents like St. Georgen am Längsee (founded about 1002–1018), Millstatt (founded between 1060 and 1091), and Ossiach (founded about 1028) could have been influenced by the fact that the lakes with their rich stocks of fish provided an excellent Lenten fare. During the last years, professional fishing ceased, and nowadays, fishing is performed nearly exclusively by sport fishers. Angling



Carinthia Lakes and Reservoirs in Austria, Photo 1 Lake Wörthersee (Photo: M. Seger, Klagenfurt).



Carinthia Lakes and Reservoirs in Austria, Photo 2 Lake Weissensee (Photo: M. Seger, Klagenfurt).



Carinthia Lakes and Reservoirs in Austria, Figure 1 Lakes, river dams, and storage reservoirs in Carinthia (Grafic: Jutta Gradenegger, Klagenfurt).

Carinthia Lakes and Reservoirs in Austria, Table 1 Morphometrical and limnological data of Carinthian Lakes (*m* meromictic, *h* holomictic, *o* oligotrophic, *o-m* oligo-mesotrophic, *m-e* meso-eutrophic)

Name of lake/ Dimension	No. in Figure 1	Attitude (m.a.s)	Area (ha)	Volume (m ³ × 10 ⁶)	Max. longitude (m)	Max. latitude (m)	Max. depth (m)	Mean depth (m)	Shorelength (km)	Theor.water renewal time (year)	Mixis- type	Trophic state
Wörthersee	1	439	1,938.8	816.4	16,500	1,700	85.2	41.9	42	10.5	m	o-m
Millstätter See	2	588	1,328.1	1,204.6	11,500	1,800	141	88.6	25.5	7.5	m	o
Ossiacher See	3	501	1,078.7	206.3	10,380	1,540	52.6	19.6	25	1.8	m	o-m
Weißensee	4	929	653.1	226.1	11,400	900	99	35.1	24.8	9.2	m	o
Faaker See	5	554	220.0	35.2	2,100	1,700	29.5	16.1	7	1.8	h	o
Keutschacher See	6	506	132.7	13.6	2,074	1,114	15.6	10.3	6.1	0.75	h	o
Klopeiner See	7	446	110.6	25.4	1,750	800	48	23	4.5	11.5	h	o-m
Längsee	8	550	74.8	9.19	1,270	862	21.4	13.4	3.8	9.7	m	o
Pressegger See	9	560	55.3	1.88	950	600	13.7	3.4	2.9	0.05	h	o
Afritzer See	10	752	48.8	6.93	1,728	380	22.5	14.2	4.3	1.7	h	o-m
Turnersee	11	481	44.2	3.31	930	660	13	7.5	2.5	1.2	h	o
Feldsee	12	739	41.2	6.27	1,250	400	26.3	15.4	3.2	2.5	h	o-m
Gösselsdorfer See	13	469	32.0	0.61	750	600	3	1.9	2.2	0.1	h	o
Forstsee	14	601	29.0	6.50	900	500	35	22	3.4	1	h	o-m
Strussnigteich	15	552	23.7	0.24	700	500	2	1	2.1	1	h	m-e
Wangenitzsee	16	2,465	21.6	3.49	700	350	48	16.2	2	1.3	h	o
Turracher See	17	1,763	19.4	2.64	750	400	33	13.6	2.2	1.1	h	o

Carinthia Lakes and Reservoirs in Austria, Table 2 Chemical composition in the mixolimnion during spring mixing (March, April, May). Average over the period from 2003 to 2005

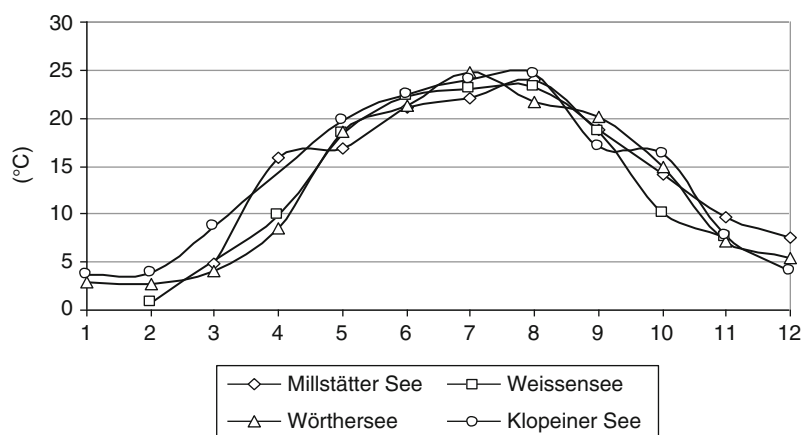
Name of lake/ Dimension	Secchi- Depth (m)	pH	Conductivity (µS/cm)	Acid-binding- capacity (mmol/l)	Total Phosphorous (µg/l)	NO ₃ -N (µg/l)	NH ₄ -N (µg/l)	Silica (mg/l)	HCO ₃ - (mg/l)	Chloride (mg/l)	Sulphate (mg/l)
Wörthersee	3.1	7.9	315	2.8	14.1	99	8	3.2	170.8	8.8	13.0
Millstätter See	5.6	7.7	175	1.7	9.8	169	8	1.9	102.6	2.3	9.8
Ossiacher See	4.8	7.8	244	2.2	9.3	457	8	4.4	135.3	4.4	12.7
Weißensee	11.0	8.1	299	3.2	5.0	67	6	2.1	192.9	0.9	10.4
Faaker See	9.1	8.0	372	3.4	5.3	251	20	2.8	204.7	3.3	30.0
Keutschacher See	5.9	7.9	324	3.3	8.2	188	218	5.0	203.8	3.3	6.6
Klopeiner See	6.7	7.8	275	2.9	63.2	28	695	2.2	174.4	3.5	4.4
Längsee	4.6	8.0	417	3.9	21.4	81	733	2.7	239.3	11.4	16.5
Pressegger See	6.5	7.9	396	3.9	8.6	428	36	3.9	236.2	2.1	21.4
Afritzer See	3.8	7.6	164	1.4	10.3	258	21	4.4	86.1	1.4	12.5
Turnersee	4.7	7.9	375	3.7	10.5	911	465	3.1	224.0	7.7	7.7
Feldsee	3.9	7.5	128	1.0	9.7	219	10	3.8	62.8	1.0	12.9
Gösselsdorfer See	2.4	8.2	332	3.5	9.3	49	9	0.9	215.4	2.2	6.4
Forstsee	4.1	7.9	264	2.5	12.3	931	109	4.6	152.3	6.8	8.6
Strussnigteich	ground	7.9	345	3.1	52.0	250	45	2.3	190.0	4.9	14.2
Wangenitzsee	15.0	6.8	27	0.2	5.0	168	20	0.5	10.4	0.5	3.1
Turracher See	4.9	7.4	138	1.3	7.3	238	9	2.2	81.7	5.2	4.2

is a prominent part of touristic attractions. Relicts of lake dwellings in Keutschacher See testify an early settlement since Bronze Age ("Hallstattzeit").

The touristic attractions at the lakes contain any kind of water sports. Generally motorboats on lakes are prohibited: exceptions exist for regular shipping routes on the four large lakes, as well as for professional use including fishing, Taxis, fire fighters, etc. A limited number of licenses for private boats are distributed at

Wörthersee and Ossiacher See, but additional boats are not allowed. Sailing is permitted on all of the large lakes.

All the lakes are situated beyond the main discharge lines and are not fed by the river Drau and its dominant tributaries. The catchment areas of the lakes are small, and as a consequence, they have a low rate of water exchange. For example, Wörthersee needs theoretical 10.5 years for a complete renewal of the water body, Klopeiner See 11.5 years, respectively.



Carinthia Lakes and Reservoirs in Austria, Figure 2 Development of temperature stratification [°C] in four Carinthian lakes (Kärntner Institut für Seenforschung).

Peculiar limnological features

Temperature regime

The low rate of water exchange, the weak winds in valleys and basins, where lakes are situated, and an intensive solar radiation during the summer are causes for high surface temperatures up to 25°C in the epilimnion and even up to 28°C in littoral zones. Characteristic is a strict temperature-induced stratification with a reduction of temperature to 4°C in the metalimnion within a few meters (Figure 2). The high surface temperatures during the period of May till September – when most lakes in low altitudes are well suited for swimming and various water sports – are reason for the development of an intensive summer tourism.

When bad weather approaches during autumn, the water cools down rapidly, and the smaller the surface of a lake, the earlier it freezes. In small lakes, the ice cover sets in during November or December, whereas large lakes freeze normally in January. No ice coverage occurred on the large lakes Wörthersee, Millstätter See, and Ossiacher See during mild winters. In contrast, the small lakes freeze every year. The thickness of the ice changes considerably from year to year and attains, in most cases, 20–30 cm. The ice offers a lot of opportunities for winter sports, especially skating. The period of ice coverage varies in lakes situated in valleys and basins between 3 weeks up to 3 months, depending on weather conditions and altitude. Lake Weissensee is situated at an altitude of 930 m and is covered for 4 months, whereas the ice persists for 6 months on Turracher See at an altitude of 1,763 m.

Meromixis

A peculiarity of Carinthian lakes is their meromictic type of mixing. Tables 1 and 3 contain a list of the meromictic lakes Wörthersee, Millstätter See, Weissensee, Klopeiner See, and Längsee. The shelter from winds and the low flow rate are reasons of meromixis. The phenomenon of meromixis was described first by Findenegg (1933). The

discovery of meromixis has been described by Findenegg in the following way (translation of the original text in German):

“During the winter 1931/32 I investigated the variation within the stratification of carinthian lakes somewhat comprehensively. The result can be summarized that the majority of these lakes do not exhibit the expected full circulation at the beginning and end of the winter stratification, but that the deep water body remains all year long in permanent stagnation, thereby causing exceptional high O₂ depletion in the lower hypolimnion. Although those lakes belong without doubt from the aspect of production to the group of oligotrophic lakes, one detects in the depth such small quantities of O₂, that even extremely eutrophic waters with regular circulation patterns are fairly exceeded.

This is combined with a relevant formation of sapropel in deep regions and sometimes even with a not insignificant H₂S content. It is appropriate to use the expression pseudo-eutrophic for these conditions within the deep parts of the hypolimnion.

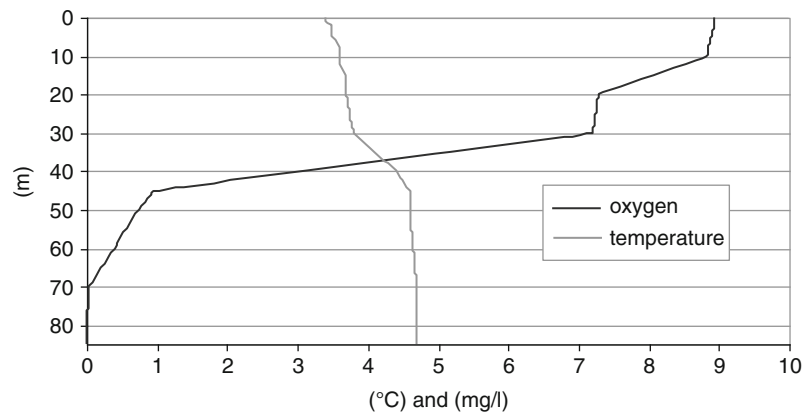
Of course it is not intended, to predetermine with this term the productivity of the lake; rather according to the trophic status, those lakes belong to the oligotrophic type and it is the intention to categorize by hydrographic means a lake in which the conditions occur due to the permanent stagnation of deep strata, as this is typical for highly eutrophic lakes during the late summer.

The appearance of pseudo-eutrophic oxygen stratification can be seen in all carinthian lakes that are either rather small but not as shallow as the Klopeiner See, or in larger lakes with considerable depth whose basins are rather elongated and narrow, as is the case in most inner alpine lakes.”

For the meromictic cycling of Carinthian lakes, the factors low flow-through-rate, position in wind sheltered basins, and a certain relation between depth and surface area are important. The actual range of mixing depends

Carinthia Lakes and Reservoirs in Austria, Table 3 Characteristics of meromictic Carinthian Lakes

Name of lake/Dimension	Area (ha)	Max. depth (m)	Mean depth (m)	Extension of mixolimnion	
				av. (m)	max. (m)
Wörthersee	1,938.8	85.2	41.9	40.0	70.0
Millstätter See	1,328.1	141	88.6	60.0	100.0
Weißensee	653.1	99	35.1	40.0	80.0
Klopeiner See	110.6	48	23	15.0	25.0
Längsee	74.8	21.4	13.4	9.0	21.0



Carinthia Lakes and Reservoirs in Austria, Figure 3 Stratification of temperature [°C] and oxygen [mg/l] in the meromictic Lake Wörthersee during the spring mixing period (11.03.1981) (Kärntner Institut für Seenforschung).

on the weather conditions that are changing from year to year (Findenegg, 1933, 1937; Frey, 1955; Harmsworth, 1984). A typical stratification of temperature and oxygen during mixing period is shown in Figure 3.

During the past years, occasionally full mixing occurred in several lakes. The reason may be seen in a short period of ice cover due to climatic changes.

Plankton and benthos

Though the plankton in various types of lakes is considerably heterogeneous, a certain general character can be recognized. In oligotrophic lakes like Weissensee, Faaker See, and Klopeiner See, the dominant algal groups consist of Bacillariophyceae, Dinophyceae, and Cryptophyceae. In weakly mesotrophic (oligo-mesotrophic) lakes, the dominant algal groups are pennate Diatomeae, Cyanophyceae, Chlorophyceae, and Cryptophyceae.

A peculiarity of strictly stratified meromictic lakes is the occurrence of *Planktothrix rubescens*. No other organism of Carinthian lakes caught so much interest in scientists as well as in the public community. Popularly, it is called “red algae.” It was observed for the first time in 1906 at Wörthersee; in relevant quantities it appeared during the 1930s and colonized primarily Wörthersee, Keutschacher See, and Längsee. In 1959 and 1960, it was recorded for Ossiacher See, in 1961 for Millstätter See, and in 1962 in Wörthersee in larger quantities and

even in form of algal blooms. The organism exhibited a significant behavior. During late autumn and winter, when the cycling of water masses had already initiated, the species is distributed uniformly within the whole water body. One can recognize that phenomenon with bare eyes because at that time the lakes contain a considerable turbidity and a rusty brown or brownish color.

After freezing these primarily, singular filaments clump together and can be recognized below the ice as red flakes. In spring, after the melting of the ice, *Planktothrix* becomes again distributed uniformly throughout the entire water body after the mixing process. With the warming of the surface water and the increasing radiation, the species starts to withdraw from the surface and retires into the metalimnion. As a consequence, the epilimnion is nearly devoid of *Planktothrix* filaments since May or June. During the whole summer, this algal species spends in the metalimnion and concentrates between 10 and 12 m to maximal densities of 92 g/m³, where it attains a good development in spite of the unfavorable light conditions. *Planktothrix* deprives the epilimnion from a considerable amount of nutrients, and therefore, the epilimnion remains poor in nutrients, contains a low biomass of phytoplankton, and reveals a high transparency (Kärntner Seenerichte 1975 till now, every year).

Planktothrix showed this behavior for many years. When the nutrient levels of the lakes increased during

the 1960s because of increasing wastewater discharge, this kind of behavior switched totally. Their biomass increased and the zones of maximal density were dislocated from the metalimnion to the surface. This could be observed for the first time in Wörthersee in 1963. At the peak of eutrophication – in the years 1968 till 1972 – the species came to the very surface in the summer. The entire surface of Millstätter See was covered with a thick layer of reddish-brown flakes and aggregates. The same phenomenon occurred in other lakes as well, creating disgusting aggregations. Since the construction and finishing of sewer systems lead to a marked decrease of nutrient levels, *Planktothrix* switched again to its normal behavior – stratifying in the metalimnion. The entire surface of Ossiacher See was covered by algal blooms of *Anabaena flos-aquae* and *Microcystis aeruginosa* during the period of enhanced eutrophication from 1971 to 1972. Since the construction of sewer systems, these phenomena did not occur any more.

The zooplankton consists of following genera/species:

1. Rotatoria: *Polyarthra*, *Keratella*, *Kellicottia*, *Filinia*, *Trichocerca*, *Pedalion*, *Pompholyx*, *Ascomorpha*, *Synchaeta*, *Gastropus*, *Asplanchna*
2. Cladocera: *Daphnia hyalina*, *D. longispina*, *D. cucullata*, *D. galeata*, *Bosmina coregoni*, *B. longirostris*, *Diaphanosoma brachyurum*, *Ceriodaphnia quadrangula*, *Leptodora kindtii*, *Bythotrephes longimanus* (only in Millstätter See)
3. Copepoda: *Eudiaptomus gracilis*, *Eudiaptomus graciloides*, *Cyclops abyssorum*, *Mesocyclops leuckarti*, *Thermocyclops hyalinus*, *Mixodiaptomus laciniatus*, *Arctodiaptomus alpinus* (only in mountain lakes)

It has to be mentioned that larvae of *Chaoborus* sp. (midge, Diptera) occur in lakes with anoxic or low-oxygen-saturated water in the hypolimnion. A biological peculiarity is the presence of the limnic jellyfish *Craspedacusta sowerbyi*, which is occasionally frequent in warm summers.

The benthic community is characterized by the occurrence of the mussel species *Anodonta cygnea*, *A. anatina*, *Unio pictorum*, and *Dreissena polymorpha*, the latter occurring in Carinthian lakes since 1972, when it was introduced by tourist boats.

Large areas of the benthal are devoid of faunal organisms due to the lack of oxygen in the profundal of meromictic lakes. In the littoral zones, the ubiquitous species of dragonflies (Odonata), chironomid midges, Oligochaeta (*Tubifex*), water snails (*Viviparus*, *Planorbis*, *Limnaea*) are present.

With the invasion of the crayfish pest – an infection of the ascomycetic fungus *Aphanomyces astaci* – the former frequently distributed freshwater crayfish species (*Astacus astacus*, *Austropotamobius pallipes*, *A. torrentium*) were extincted or strongly decreased respectively. The indigenous crayfish *Astacus astacus* has relict areas in some lakes. The former dense populations were extincted with

the introduction of the North American species *Orconectes limnosus* and *Pacifastacus leniusculus*.

The fish fauna consists of following species:

Lake trout (*Salmo trutta* f. *lacustris*), charr (*Salvelinus alpinus*, Millstätter See, mountain lakes), whitefish (*Coregonus lavaretus*), pike (*Esox lucius*), carp (*Cyprinus carpio*), bream (*Abramis brama*), white bream (*Abramis bjoerkna*), bleak (*Alburnus alburnus*), shemaya (*Chalcalburnus chalcoides mento*, only in Wörthersee), crucian carp (*Carassius carassius*), chub (*Leuciscus cephalus*), minnow (*Phoxinus phoxinus*), bitterling (*Rhodeus sericeus*), roach (*Rutilus rutilus*), rudd (*Scardinius erythrophthalmus*), green tench (*Tinca tinca*), vimba (*Vimba vimba*), wels (*Silurus glanis*), burbot (*Lota lota*), perch (*Perca fluviatilis*), pike-perch (*Stizostedion lucioperca*), loach (*Barbatula barbatula*).

Introduced species: pope (*Gymnocephalus cernuus*), pumpkin-seed (*Lepomis gibbosus*), largemouth bass (*Micropterus salmoides*), (*Pseudorasbora parva*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), eel (*Anguilla anguilla*).

As a peculiar feature is the indigenous *Coregonus lavaretus* of lake Wörthersee, which has been stocked in other regional lakes too. Charrs (*Salvelinus alpinus*) are the typical fish of alpine lakes, which attain a length of up to 15 cm in a special dwarfed form (“Schwarzreuther”) due to scarcity of food. Professional fishing is rare in Carinthian lakes, most fishing is exerted as angling, where especially lake trout (*Salmo trutta* forma *lacustris*), pike (*Esox lucius*), wels (*Silurus glanis*), and pikeperch (*Stizostedion lucioperca*) belong to the most attractive prey. Further, there is the largemouth bass (*Micropterus salmoides*) which has been introduced in 1900 and could establish stable populations only in Wörthersee and Keutschacher See among all central European lakes.

In contrast to the dense settlement along the shores of all large lakes, there remained still zones with natural vegetation, consisting of reed (*Phragmites australis*), rush (*Scirpus lacustris*), water lily (*Nymphaea alba*), yellow water lily (*Nuphar lutea*), pondweed (*Potamogeton* sp.), water milfoil (*Myriophyllum* sp.), soft hornwort (*Ceratophyllum submersum*), muskgrass (*Chara* sp.).

Eutrophication

The initiation of an intensive summer tourism in the early 1950s and the crescent prosperity of the population at the lakesides and the catchment areas induced a considerable wave of eutrophication. Overnight lodging within the catchment area of Wörthersee increased within three decades from 500,000 up to three million in the year 1980. The wastewaters were either poorly treated or directly discharged into the lakes or their tributaries. Consequences were hygienic inconveniences with enhanced numbers of fecal bacteria in littoral regions and considerable loads of phosphorous and nitrogen compounds. The concentrations of total phosphorous increased steadily.

The concentrations of phosphorous – being the limiting element for algal growth in Carinthian lakes – increased continuously. For example, the annual load of phosphorous discharged into Wörthersee was 20–22 and 23 t for Millstätter See. This continuous input of nutrients intensified the growth of phytoplankton in the epi- and metalimnion. Water transparency decreased with the growth of algal biomass, and the decomposition of algal biomass in the profundal zones consumed oxygen and decreased its content in the hypolimnion (Figure 4). The accelerated growth of phytoplankton and a spectacular lead in 1963 for the first time at the western bay of Wörthersee to mass aggregations of *Planktothrix rubescens* algal bloom. The continuous process of eutrophication culminated in many lakes in the period of 1968–1973. From 1970 to 1973, an algal bloom of *Planktothrix rubescens* covered the entire surface of Millstätter See. In Ossiacher See, the bloom consisted of *Microcystis aeruginosa* and *Anabaena flos-aquae* and covered the entire surface too. Other lakes had mass developments of macrophytes (Afritzer See, *Elodea*

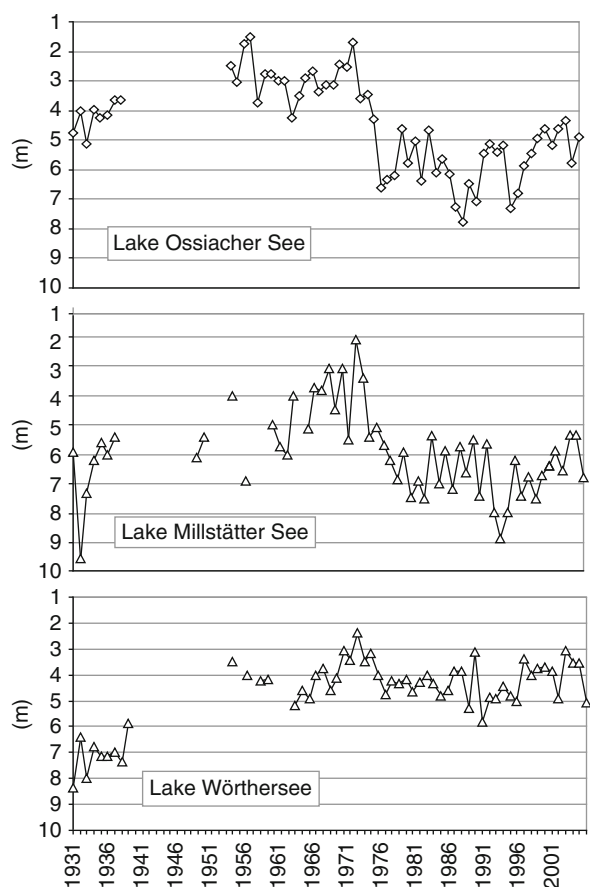
canadensis), and in some lakes, the proceeding of eutrophication was visible in the growing deficit of oxygen in the hypolimnion.

Sanitation

The pressure of deficits in water quality since 1963 – hygienic problems in the littoral, large-scaled algal blooms covering entire lakes – evoked projects for the prevention of wastewater discharge by construction of sewer systems. All wastewaters of domestic origin within the hydrographic catchment area were collected in sewer systems and drained to wastewater treatment plants. Those plants were situated at the lakes runoff or at other rivers, preventing a further loading of lakes with their nutrients. This was possible in the Carinthian lake district, as the catchment areas of lakes are fairly small. With this concept, even a residual loading from cleared wastewaters was eliminated. The sewer systems were constructed according to a principle, that collectors are situated either on land or in form of pumping lines within the lake, where the wastewater is transferred from pumping station to pumping station. The tubes used in the lakes are plastic pipes that were extruded at the lake in the form of endless tubes and then sunk to the ground.

For the management of the sewerage projects, so-called sewage associations were established that organized engineering, planning, construction, and financing as well as the maintenance of the sewer systems. The peculiarity of this kind of lake sanitation was the complete avoidance of residual loading by wastewater and, according to technical and topographical opportunities, the installation of pumping lines at the bottom of a lake. The fundamental principle was the establishment of sewer systems in the entire catchment area of the various lakes.

With the collection of wastewaters in sewers, the hygienic situation at littoral sites improved immediately, and all limits and guide values of the “Directive on the quality of bathing water 76/160/EEC” as well as the Austrian law “Badegewässerverordnung, BGBl. (BGBl. II 429/2009)” are fulfilled at any time, and the values fall by far below the limits. There are no objections with



Carinthia Lakes and Reservoirs in Austria,
Figure 4 Development of Secchi depth [m] since 1931 (annual average) in the three large Carinthian Lakes (Kärntner Institut für Seenforschung).

Carinthia Lakes and Reservoirs in Austria, Table 4 Storage reservoirs

Storage reservoirs	No. In Figure 1	Altitude m.a.Sl	Area ha	Max. depth m
Kölnbrein	18	1,902	255	200
Speicher Soboth	19	1,080	80	80
Speicher Hochwurtten	20	2,417	50	52
Oscheniksee	21	2,391	45	172
Stausee Freibach	22	729	32	40
Zirmsee	23	2,529	30	49
Grosssee	24	2,417	30	102
Speicher Galgenbichl	25	1,704	27	50
Grosser Mühdorfer See	26	2,319	24	39
Speicher Gösskar	27	1,704	12	55
Kleiner Mühdorfer See	28	2,379	11	37

Carinthia Lakes and Reservoirs in Austria, Table 5 River dams

River dams	No. In Figure 1	Altitude m.a.sl	Area ha	Length (km)	GWh	Year of opening
Paternion	29	515.0	70	6.0	95	1988
Kellerberg	30	505.3	101	9.8	96	1985
Villach	31	495.6	102	10.2	100	1984
Rosegg – St. Jakob	32	485.5	413	17.2	338	1974
Feistritz – Ludmannsdorf	33	461.5	467	14.6	354	1968
Ferlach – Maria Rain	34	437.8	353	10.6	318	1975
Annabücke	35	416.4	438	14.5	390	1981
Edling	36	390.8	1,115	24.0	407	1962
Schwabegg	37	369.0	232	24.0	378	1943/1995
Lavamünd	38	368.7	86	6.2	156	1945/1949

respect to the hygienic conditions (EU-Report: “Quality of bathing water,” yearly). With the limitation of anthropogenic nutrient inputs, the concentration levels of phosphorous and algal biomass improved continuously. Algal blooms of cyanobacteria (blue-green algae, Cyanophyceae) did not occur since then, and the water transparency increased since the summit of eutrophication (between 1969 and 1972, Figure 4) significantly yet in individual patterns. The re-oligotrophication process is described by Sampl (1982), Sampl et al. (1982), and Kärntner Seenbericht (1975) till now (every year).

As additional actions of lake sanitation (restoration, therapies, internal actions), the following were executed: removal of sediments with high nutrient contents (Ossiacher See, Pressegger See), aeration of the hypolimnion (Feldsee), draining-off of hypolimnic water (Klopeiner See), and removing an excess of macrophytes.

The province of Carinthia achieved in 1991 the “Tourism for tomorrow award” (European winner 1990 for clean lakes in Carinthia) for its successful restoration of Lakes.

Storage reservoirs

Storage reservoirs have been constructed in the high alpine regions for the generation of hydroelectric power in storage power stations and exhibit ecological characters similar to natural lakes. The important differences are focused on the runoff which is situated at the bottom and huge amplitudes of water levels. Reservoirs attain considerable size and depth (Figure 1, Table 4) and contain a composition of phyto- and zooplankton species which is not significantly different to that in natural lakes. The main genera of phytoplankton are Bacillariophyceae (*Synedra* sp.) and Dinophyceae (*Gymnodinium* sp.), Chlorophyceae, Cryptophyceae, and Cyanophyceae (*Phormidium* sp.). The species of zooplankton are the same like those in the lakes, additional *Arctodiaptomus alpinus*. Some reservoirs were constructed by damming up natural alpine lakes and thereby changed to reservoirs of increased size and depth (Oschentsee, Zirmsee, Großsee, Major and Minor Mühldorfer See). In accordance to the high altitudes, the period of ice coverage lasts 6–8 months and the thickness of the ice can surpass 1 m.

Benthic organisms do not occur in areas that fall dry in periods of low water level. In the residual reservoir larvae of chironomids, oligochaeta, and mussels (Fam. Sphaeriidae) are present.

Fish exhibit a poor species diversity and originate from specimens that were stocked. A self-maintaining population of charrs (*Salvelinus alpinus*) developed in some of those reservoirs; nevertheless, the population contains dwarfed individuals called “Schwarzreuther” to a high degree. Additional brown trout, rainbow trout, lake trout, and minnows have been stocked.

River dams

A series of dams were constructed at the main river Drau (Figure 1; Table 5). The reservoirs cannot be classified as lakes in the classical sense but are river courses with extremely decreased streaming velocity. Nevertheless, they cover a considerable area. The former mere technological construction of shores has been restored according to principles of biological engineering in the past years by the formation of islands and shoals.

The former bad quality of water (α -mesosaprobic) became better since cleaning the domestic and industrial wastewater. Now, the river Drau is in β -mesosaprobic condition.

The faunal composition of fish is poor in species, with bream (*Abramis brama*) being the dominant species. Other species are pike, catfish, chub, roach, rudd, green tench, burbot, perch, barbel, and nase (*Chondrostoma nasus*). Introduced: rainbow trout, pike-perch, carp, chrupe (*Aspius aspius*), and sterlet (*Acipenser ruthenus*).

The benthic community is characterized by the occurrence of Oligochaeta (*Tubifex*, *Limnodrilus*) and Chironomidae. Other groups are rare like Hirudinea, mussels (Sphaeriidae, *Dreissena*), snails (Lymnaeidae), and Trichoptera.

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Cross-references

[Alpine Lakes](#)

CASPIAN SEA

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Physical-geographical characteristic

The Caspian Sea is the largest closed water body in the world. Five states are situated on its banks: Russia, Azerbaijan, Islamic republic Iran, Kazakhstan, and Turkmenistan. The area of the sea at present equals to 0.4 million km² making 18% of the total area of lakes of the Earth. The volume of water equals to 79,000 km³. The maximal extension of the sea from north to south equals to 1,200 km, its width varies from 200 up to 450 km, and the greatest depth equals to 1,025 m.

The Caspian Sea accepts water of 130 rivers from the catchment area which is approximately ten times greater than its own one (3.5 million km²). The main feature of the hydrological regime of the Caspian Sea is significant fluctuation of its level which is the reason of significant damages and ecological accidents. The sea water level is determined by the ratio of water balance components of the water body and by possible changes of the volume of its depression ([Figure 1](#)).

According to its physical-geographical and morphological features, the Caspian Sea is subdivided into three parts: Northern, Middle, and Southern ones, and represents a huge continental depression.

The islands on the Caspian Sea occupy approximately 2,050 km². Most of the islands are located in North Caspian (more 1,800 km²). The largest among them is Chechen (122 km²), like the Tuleniy Island (68 km²), it was formed due to abruption of shallow areas during the decreasing of sea level in North Caspian.

In the eastern part of North Caspian, the Tuleniy Islands archipelago is located. Among them, Kullaly Island

(73 km²), Morskoy Island (65 km²), and many small islands can be distinguished. The majority of the sea islands of North Caspian represent accumulative formations of the bar type formed by waves on peripheral sites of raisings or structures of a sea bottom.

The Northern part of the sea is the shallowest. Its average depth is of 4.4 m. Morphologically, the border of North Caspian takes a shape of a threshold having the depths of 10–15 m. Rivers Volga and Ural flowing into North Caspian form extensive deltas overgrown by dense reed. Relic forms of river coasts, beds, and deltas are distinctive features of the morphological structure of the Caspian Sea coastal zone. The numerous relic river beds are particularly apparent in the relief of the North Caspian bottom.

Middle Caspian occupies the area of 140,000 km²; its average depth is 192 m. In this part, the sea has the least width – about 200 km. The border between Middle and South Caspian approximately coincides with 40th parallel.

The western coasts of Middle Caspian are mostly accumulative, and only several parts of the coast of Dagestan and Apsheron are abrasion ones. On the western coast, large deltas of the rivers Terek, Sulak, and Samur are located. The eastern coast of Middle Caspian is considerably lower than the western one, and there is no receipt of river sediments here. Capes and spits project from the eastern coast of Middle Caspian far into the sea, gulfs pressing into the coast between them. The biggest gulf of the Caspian Sea is Kara-Bogaz-Gol. Eastern coasts are mostly abrasion developed in limestone that composes the adjoining deserted and semideserted plateaus. In the central part of Middle Caspian (closer to the western coast), the deep Derbent depression is located with the maximal depth of about 790 m.

South Caspian has an area of 148.5 thousand km² and occupies a depression that geologically is concerned to the Alpine folding area with complex relief and the greatest depths (maximal depth is 1,025 m, the average depth is 344 m). The relief of the bottom and the shelf zone of South Caspian are characterized by numerous mud volcanoes and tectonic raisings.

The southern coast of the sea is bordered with high mountain ridge Elburus. Numerous rivers flow down into the sea from the mountains of the Iranian coast. The eastern coast of South Caspian is low up to Cheleken Peninsula in the north; deserts prevail at the seashore. To the north, the two gulfs Krasnovodsk and Turkmenian, ones divided by Cheleken Peninsula, are located.

Basic climatic features

The Caspian Sea is located within the limits of various climatic zones and is influenced by different baric centers and systems of atmospheric circulation. Local climatic features are significantly influenced by complex orography of the western and southern coasts of the sea. The greater part of the Caspian Sea is located in the moderate climatic zone. North Caspian and its coasts are located in



Caspian Sea, Figure 1 The Caspian Sea map.

a strip of continental temperate climate. The winter here is frosty, with poor snow; the summer is hot and dry. At the eastern coast of Middle Caspian, the climate is severe, of the deserted type, with insignificant amount of precipitation.

On the water area of the Caspian Sea, the atmospheric precipitation is distributed nonuniformly. Average precipitation varies from 75 mm up to 150 mm/year along the eastern coast; along the western coast, it varies from 200 mm up to 400 mm/year in the north and up to 1,200 mm/year in the south. Approximately 70% of annual norm of precipitation falls in autumn, and in winter, only 7–10% of precipitation account for the summer months. From the point of view of climate, Lencoran subtropical area is essentially different. Here, winter is soft and moist, with high air temperature, even minimal values of it fall below zero extremely seldom. Even softer is the

subtropical climate of the Iranian coast having very high humidity almost during all the year.

Wind direction and speed above the Caspian Sea are determined by general atmospheric circulation, pressure fields, and orography. Winds most often observed on the Caspian Sea are those of northwest and southeast directions with the speed of 5–9 m/s. Annual wind speed reaches the greatest values in the area of Apsheron peninsula – 6.2–8.0 m/s. Along all the eastern coast of Middle Caspian, the regime of wind speed is approximately the same. Annual wind speed is about 5.0–6.3 m/s, with the maximum in areas of Fort Shevchenko and Kara-Bogaz-Gol. In South Caspian where strong winds are observed seldom, annual wind speed makes 3.0–4.5 m/s.

Average annual air temperature in the northern part of the sea equals to 8–10°, in the middle part, it equals to 11–14°, and in the southern part, 15–17°. For the whole

sea, on the average, it equals to 13.1° . The average air temperature above all the water area in July–August is within the limits of $24\text{--}26^{\circ}$ (Gidrometeorologija, 1992).

Hydrological regime of the sea and its coastal zone

The basic role in the formation of a hydrological regime of the Caspian Sea is played by river runoff, the climate, and morphometric characteristics (sea depths, bottom relief, and the character of the coast).

Sharply contrast climate and physical-geographical features of northern, middle, and southern parts of the sea are the reasons for essential differences in the hydrological regime of them. The northern part of the sea should be marked out. Shallow North Caspian is most subjected to the influence of sweet river waters inflow and sharp fluctuations of seasonal air temperatures. Each winter, the sea here is covered by ice.

The general circulation of waters of the Caspian Sea (horizontal and vertical) is created by cumulative influence of wind, the density field, rejecting forces of rotation of the Earth, and convection. The resulting system of currents of the Caspian Sea, as well as drift and geostrophic currents taken separately, has the character of circulations of different signs.

Wave regime of the sea and its coastal zone

The Caspian Sea belongs to the seas with rough waving. Development of waves of big height is promoted by strong storm winds of northern and southern directions and great meridional extent of a water body. The maximal wave heights in the open sea during strong storm in 1954 reached 14 m.

Storm processes are especially intensive in autumn and winter in North Caspian. In the middle part, the most intensive waving is observed under northwestern winds (in Apsheron region, the maximal wave height with recurrence of 1 times per 50 years can reach 15–17 m). To the northeast from Makhachkala, waving is stronger under southeast winds.

Water balance and the sea level – long-term fluctuations

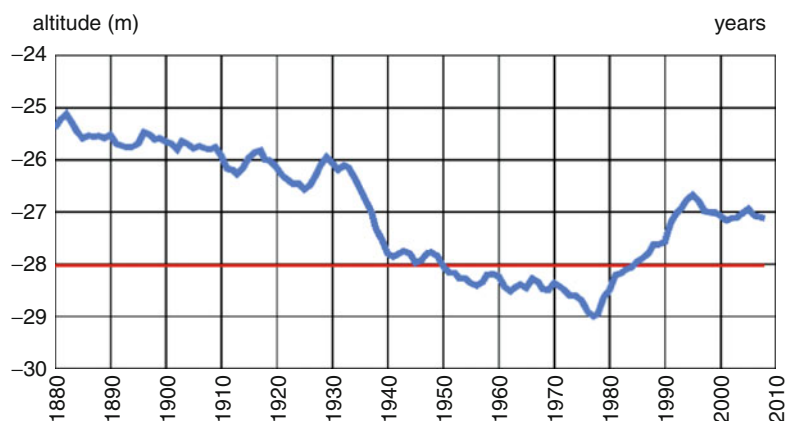
For the period of instrumental observations from 1830 until present time, the amplitude of fluctuations of the sea level has made 3.8 m; the highest standing of the level was registered in 1882, which was -25.2 m; the lowest one – in 1977 – was -29.0 m. In 1995, the average annual level was equal to -26.51 m. Three time periods can be distinguished, having sharply different regimes of the sea level: the first is prior to the beginning of 30th years of the previous century; the second, up to 1977; and the third, from 1978 till now. The first of these periods that lasted for about a hundred years had the most steady characteristics of the level with annual average value being nearby -26.1 m (Figure 2).

For the second period, sharp enduring falling of the sea level is characteristic. Since 1930, the sea levels dropped annually, and until 1941, annual decrease of the level made 16 sm. Later, the level on the whole continued falling replaced by small rises in some years. The general decrease of the sea level during the whole second period has made 2.8 m. In 1977, the sea level reached the lowest mark for all the period of instrumental measurements (-29.0 m).

For the third period, since 1978, continuous (during 18 years) rising is characteristic at an intensity of about 14 sm a year. The rising of the level in 1995 made 2.5 m. Fluctuations of water balance components of the sea lead to seasonal and long-term fluctuations of the water level of a closed water body. Water balance equation for the Caspian Sea in the most simple form is written as follows:

$$P + Q - E - Q_{KB} = w, \quad (1)$$

where P is the precipitation on the sea surface, m^3/year , Q is surface and underground inflow to the sea, m^3/year , E is the evaporation from water surface of the sea, m^3/year , q is the runoff into Kara-Bogas- Gol, m^3/year , w is the change of water volume in the sea, m^3/year .



Caspian Sea, Figure 2 Fluctuations of The Caspian Sea level over the period of instrumental observations.

In the receipt part of water balance, the basic role is played by river runoff, especially that of Volga making approximately 80% of the total water inflow into the sea. Available data of long-term instrumental observations show that fluctuations of river runoff are characterized by grouping of high-water and low-water years. Such series (grouping) can proceed for up to several decades, significantly determining fluctuations of sea water level.

The volume of underground runoff into the sea is estimated on the basis of special hydrological researches, it makes no more than 3–6 km³ per year, which is only about 1/1,000 of the evaporation losses from the whole Caspian Sea. Outflow of sea water into Kara-Bogaz-Gol is determined basically by a difference of water levels between the sea and the gulf.

The major element of the expense part of water balance of the sea is evaporation from water surface. Direct measurements of evaporation from the sea are impossible. Estimation methods and special in situ researches allow estimating evaporation using standard meteorological observations from coastal and island stations, by ships, and sea platforms. The average layer of an annual evaporation makes 960 mm of water.

Principal reasons for sea level changes are climatic ones. Interannual changes of humidification of the watershed, including water area of the sea, cause changes in river runoff volumes, in amount of precipitation, and in evaporation from the sea surface.

The outflow from the sea into the Kara-Bogaz-Gol Gulf impacts essentially on sea level fluctuations. The water discharge into the gulf depends on the difference between the sea level and the gulf water level. As much as 20–25 km³ of water per year can be evaporated from the gulf water surface. In 1980, a dam between the sea and the gulf was built for the purpose of sea level stabilization. Due to this action, the outflow into the gulf was stopped, and the gulf was dried up completely during several years. In 1992, the dam has been destroyed to prevent the sea level growth, and the water exchange between the sea and the gulf has been restored.

Modern estimations of the sea water balance are following: the river water inflow is 315 km³ per year, the visible evaporation (evaporation minus precipitation) is equal to 0.75 m per year.

Seasonal fluctuations of the sea level

Depending on rivers runoff and evaporation from water surface, intra-annual (seasonal) fluctuations of the level are characteristic for the sea. The magnitude of fluctuations is defined basically by river runoff which is noted for its great seasonal variability. From April till June, due to river runoff, the basic rising of sea level takes place, and in June, the maximum is usually observed. Since July–August when river runoff is considerably reduced and evaporation increases, the sea level drops to the winter minimum in December (Middle and the South Caspian), in January–February (North Caspian). Annual average

amplitude of seasonal fluctuations of the sea level equals to 30 sm, but in North Caspian, it reaches 40 sm.

Short-term changes of the sea level

Short-term fluctuations of the sea level are tidal (periodic), seiche, baric, and set-up and set-down fluctuations.

Seiches characterize natural fluctuations of a sea level as a closed reservoir. The measured periods of seiche make 2.7–3.0, 4.4–4.7, and 9.0–9.5 h; some of them are observed only at the eastern coast (9–9.5 and 24 h), seiche with the period of 24 h having breeze character. In shallow northern part of the sea during the passage of cyclones, level fluctuation of the synoptic period (from 4 to 12 days) is observed.

Windwave changes of the sea level being often observed during the development of severe storms are the most dangerous. In North Caspian, because of extensive shoals favorable conditions develop for the formation of significant set-up and set-down level fluctuations not exceeding 10–20 cm in deep parts of the sea. In the coastal zone of the western part of North Caspian, frequent continuous southeast and east winds are the reasons for annual set-up from 0.5 m up to 1–1.5 m and for set-down of the same height at the eastern coast. Extreme values of the sea level deviations from static horizon before a storm can reach 4.5 m. The shore during the maximal development of such a set-up has been flooded on 25–50 km.

Long-term forecasting of long-term fluctuations of the sea level

The forecast of water level fluctuations of the Caspian Sea is the most complicated geophysical problem. It demands knowledge of mechanisms of the origin of long-term fluctuations of the climate and the river runoff. Poor predictability of long-term dynamics of hydrometeorological processes today allows estimating only probability characteristics of future fluctuations of the Caspian Sea level.

The water balance mechanism of level fluctuations of a closed water body consists in the following. The water received by a water body in the form of river inflow and precipitation, is spent basically on evaporation. When total water inflow exceeds evaporation, the level of a water body grows, that leads to the increase of the area of the water surface and, accordingly, to the growth of evaporation. If evaporation exceeds the inflow, the level drops and the evaporating surface decreases. Correspondingly, the evaporation decreases leading to the deceleration of the rate of water level decreasing. As the result, in stationary climatic conditions, the level of an internal closed water body fluctuates around the position adequate to the balance of annual average sizes (volumes) of inflow and evaporation (the so-called level of gravitation) (Krickij et al., 1975).

The problem of the forecasting of a closed water body level is reduced to the probability forecast of processes of river runoff and evaporation and the account of positive

and negative relationships in the system under investigation described by the stochastic differential equation of water balance. Forecast estimations, as a rule, are received by the method of imitating modeling.

Ice regime of the sea

The Caspian Sea is partially freezing water body, and shallow northern part of the sea becomes frozen annually. In the middle part, ice appears along the coasts only during severe winters; in the southern part of the sea ice does not appear.

In winters with normal temperature conditions, ice formation starts in shallow eastern areas of North Caspian in the first half of November. Further, it extends westwards, covering almost simultaneously shallow western area and the Volga beach.

In cold and extremely cold winters, stationary ice is established on the whole water area of North Caspian up to the depths of 20 m. In very warm winters on the greater part of North Caspian, steady freezing does not occur.

The important role in the establishment of ice cover on North Caspian is played by ice drift. Ice drift occurs mainly from east to west and southwest along the edge of the fast ice and along the western coast of the Caspian Sea. The speed of general drift of ice is about 7 km/day. The process of ice cover destruction and clarification in North Caspian proceeds in spring in the direction reverse to that of ice formation – from the south to the north.

Maximal thickness of ice of natural increase as a rule does not exceed 60 sm in the northwestern part of the sea and 90 sm in the northeastern part.

Ice cover in the sea is more often represented in the form of stratifications. Strong winds, especially in an initial stage of ice cover formation, promote to breaking of fast ice and to its intensive motions. At the thickness of ice from 1 up to 30 sm, its repeated stratification and hummocking take place.

The height of hummocks makes 1–2 m; in some places, it reaches 3 m. Hummocks are often allocated in ridges

with the length of from one up to several km and with the width of some tens of meters. Ridges settle down approximately perpendicularly to dominating winds.

In the initial stage of ice cover forming, when the border of young ice extends from the coast up to the depths of 2–3 m, during ice motions, there are formed hummocks sitting on the ground – stamukhas. Stamukhas differ according to time and place of their occurrence, and also by the type of ice they are formed of.

Stamukhas of *autumn origin* have, as a rule, small size in diameter (5–20) and height of 1–3 m. Such stamukhas are formed everywhere in a coastal strip of the sea (from water edge up to the depths of 1–2 m) along northern and eastern coasts of the Caspian Sea.

Stamukhas of winter origin are formed of ice having 20–70 cm thickness, and can reach 100–300 m, sometimes 500 m in diameter and the height of 10 m. The Maximal registered height of stamukha makes 20 m.

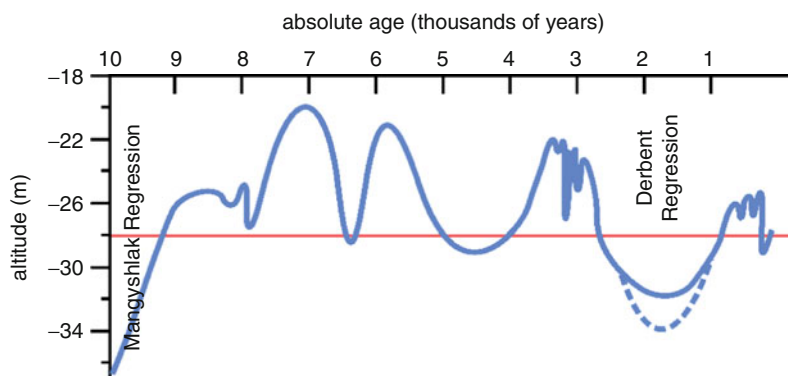
Paleogeography of the Caspian sea

Paleogeography of the Caspian Sea in Pleistocene (~800, 000 years) is characterized by sharpness and large scale of fluctuations having led to changes of water environment parameters and replacement of faunistic communities and vegetation that distinguishes the Caspian Sea from open seas (Rychagov, 1997).

According to modern concepts, the contemporary Caspian Sea is now in a deep regressive stage concerned to begin at the end of Pleistocene; since that time, the level of the Caspian Sea did not reach 0 m absolute heights. As a whole, the Caspian Sea in Pleistocene is characterized by higher standing of the sea level.

In Quaternary history of the sea, such transgressive epochs as Bakinian, Early Khazar, and Khvalynian ones can be concerned as the events of the same order; they were separated by deep and long regressive epochs.

The beginning of Pleistocene in the Caspian Sea was marked by rather long (about 100, 000 years) epoch of low standing of the level – *Turkianian Regression*. The sea level went down up to absolute height – 150 m. Some rivers of the southern slope of the Big Caucasus have



Caspian Sea, Figure 3 Fluctuations of The Caspian Sea level over the past 10,000 years (according to Rychagov, 1997).

deepened their valleys up to this depth. All water volume of the Turkianian Basin was concentrated in Southern Caspian and Middle Caspian depressions, between which there was a shallow strait in the area of Apsheiron threshold.

The regression was replaced by large and long transgression which included the middle and the end of early Pleistocene – *Bakinian Transgression*. In the opinion of many researchers, the Bakinian epoch was characterized by two transgressions – Early Bakinian and Late Bakinian, separated by the regression. The level of Late Bakinian Sea hardly exceeded the marks of 5–10 m absolute height.

The second large transgressive basin in Pleistocene history of the Caspian Sea is Middle Pleistocene – *Early Khazar Transgression*, not yielding to the Bakinian one in size and level position. The end of the Khazar stage of development of the Caspian Sea (the middle of Late Pleistocene) was marked by deep regression – *Atelian*. At that time, extensive areas of the Caspian shelf, especially in the north of the Caspian Sea, were drained; there was an intensive incision of rivers (the depth of Volga incut in its estuary part made some tens meters, and within the region of Volgograd, it made 20 m).

Atelian regression was replaced by *Khvalynian Transgression* – the third and the last large increase of the Caspian Sea level that took place in the second half of late Pleistocene. The total area of Khvalynian Sea is estimated to be 950, 000 of k km².

Waters of Khvalynian transgression had drainage into the Black Sea depression. In the opinion of the majority of researchers, the drainage has begun after the level of the Caspian Sea has received the marks exceeding Manych threshold (45–50). Late Khvalynian transgressive stage during the period of its maximal development had a level about 0 m absolute heights. In the north, its waters have occupied significant territory.

Post-Khvalynian Regressive Stage has begun in Early Holocene and is lasting now. It consists of several regressive and transgressive phases and oscillations, such as: Mangyshlak regression, New Caspian transgression, and modern regression including present increase of the level as well (Figure 3).

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Cross-references

[Aral Sea](#)
[Classification of Lakes from Hydrological Function](#)
[Water Balance of Lakes](#)

CHAD LAKE

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Introduction

Lake Chad lies in an endorheic basin located in the center of Africa and is on the southern margin of the Sahara in the semiarid Sahel belt. It is a highly variable shallow lake centered approximately on 13°30'N and 14°E (Figure 1). During the last century, its water area has varied between 1,700 and 25,000 km² in accordance with the changes in rainfall over its basin. When dealing with Lake Chad, it is thus necessary to specify the period considered.

The lake belongs to Chad, Niger, Nigeria, and Cameroon. It provides a wealth of natural resources (supporting fisheries, recession cultivation, and rangeland) that are highly attractive to many populations in the region, especially during drought years.

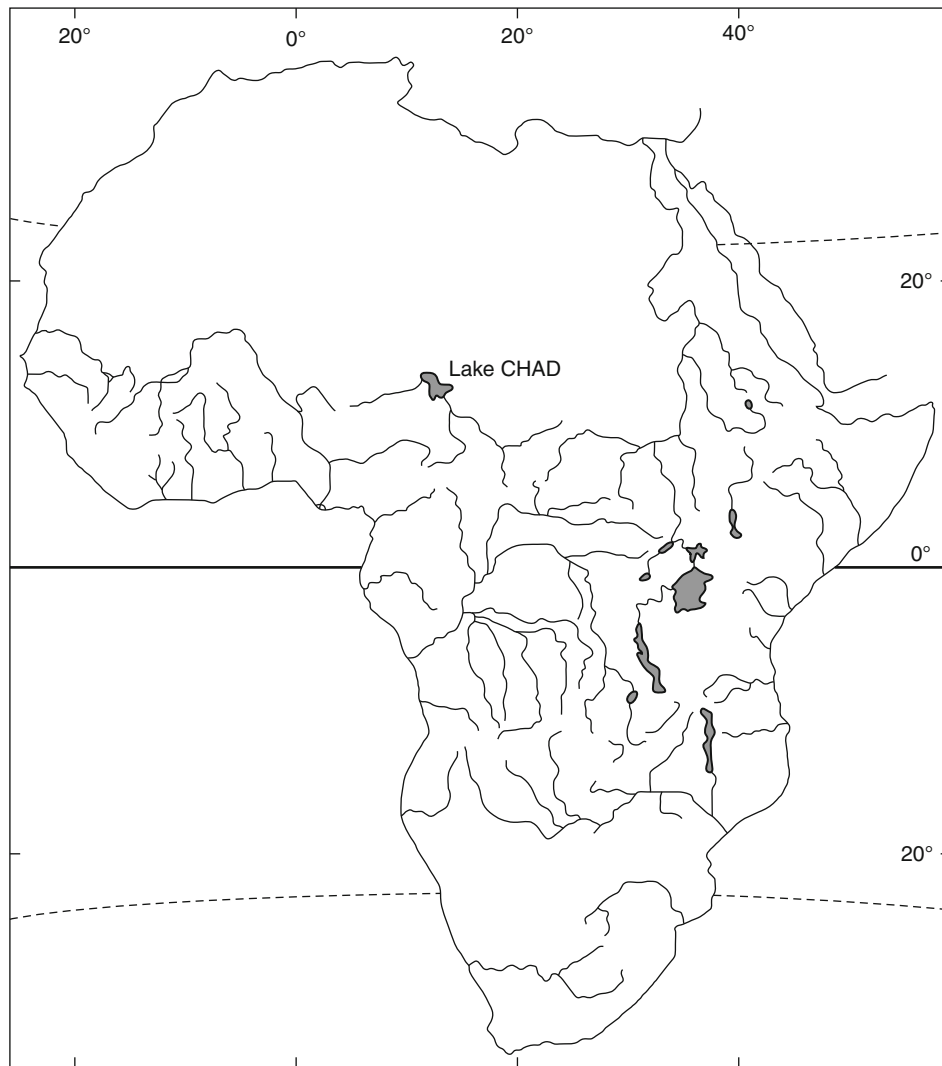
Lake Chad: variability and landscapes

Lake Chad has a long history of wet and dry periods spanning different time scales. During the late Quaternary, the last Holocene lacustrine transgressions, interspersed with dry shorter episodes, occurred between 8,500 and 6,300 BP (when the water level reached up to 325 ± 5 m asl and the lake extent 340,000 km²) and around 3,200 BP (287–290 m asl) (Servant and Servant, 1983; Leblanc et al., 2006a, b).

Over a shorter time scale, during the last millennium, data from sediment analyses and other historical records indicate a similar succession of high (up to 285 m asl) and low levels, with four to five drought periods between 900 and 1900 AD. A very dry period of 25–30-year duration at the end of the fifteenth century has been well documented (Maley, 1993).

Since the beginning of the nineteenth century, European explorers have described Lake Chad either as a very large body of water or an extensive partly dried marsh. A classification into three main states for the lake was proposed by Tilho (1909–1910), who showed that the large variations in lake level and landscapes were directly related to rainfall changes in its basin:

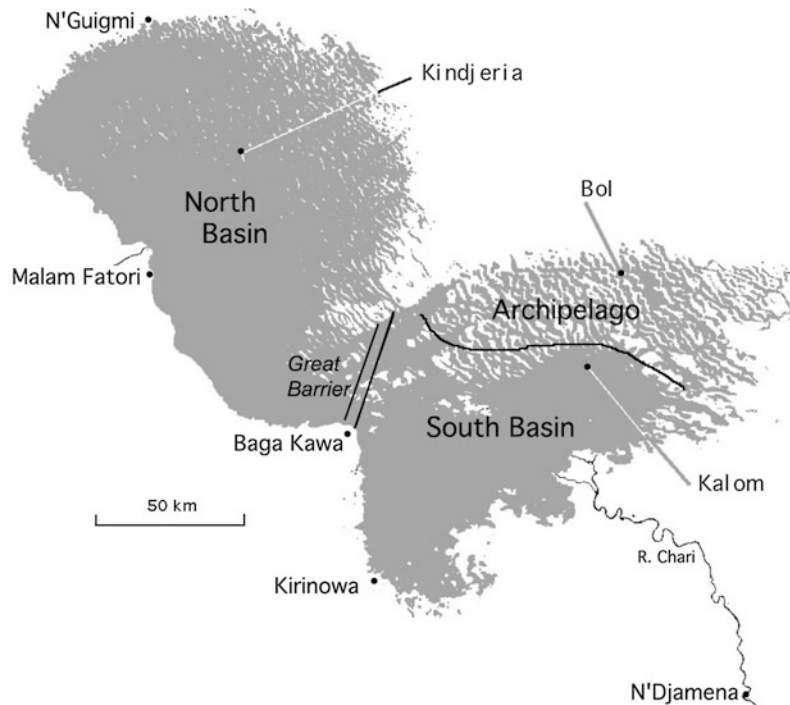
- The *Large Lake Chad* spans across 24,000 km² of open water with a limited coastal sand dune archipelago and occasional slight overflow toward the northeast through the Bahr El Ghazal at the extreme east of the lake which leads to the Bodele depression, some 500 km to the NE



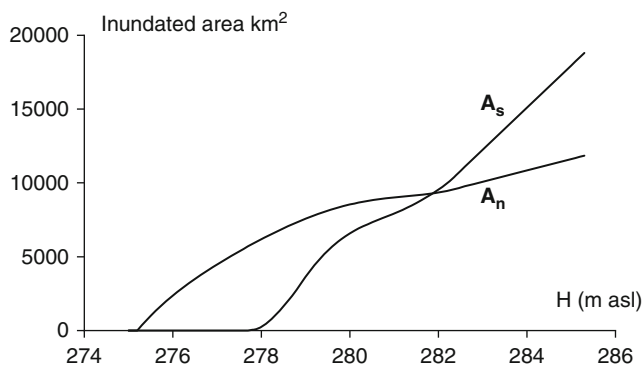
Chad Lake, Figure 1 The location of Lake Chad in Africa at the southern border of the Sahara.

and some 120 m lower. This Large Chad state has occurred only for short periods during the last century and for the last time in the mid 1950s.

- The *Normal (intermediate) Lake Chad* is a single body of water covering about 18,000 km², at an intermediate water level of about 280–282 m asl, with an archipelago of some 2,000 dune islands and a limited marshy vegetation on the shores (Figure 2). The lake is divided into two main basins separated by a shallow and narrow belt, the Great Barrier. On the northeast side of both basins, the lake is bordered by an erg of ancient dunes, the altitude of which progressively decreases along a northeast-southwest axis. This creates an archipelago of sandy islands, with a decreasing altitude toward the open waters of the two basins. In the Normal state, the total lake is composed of an extended archipelago and large areas of open water covering about 4,000– 6,000 km² in each basin. The increase in total inundated area is about 2,000 km² for a change in water level of 1 m around 281 m asl, with the northern basin having much steeper shores (Figure 3). The depth encountered in the central zones of the two basins is about 5.3 m in the northern basin and 2.7 m in the southern basin. At water levels of 280 and 282 m asl, the mean depth is 2.1 and 3.5 m, respectively (Bader et al., 2011). The Normal Lake Chad state occurs when the annual discharge from its main tributary, the Chari River, is comprised between 34 and 43 km³/year. The last shift from Normal to Small Lake Chad occurred in 1973–1975 (Figure 4).
- The *Small Lake Chad* is made up of different separated bodies with a permanent open water pool of about 1,700 km² at a maximum altitude of 280–281 m asl in front of the delta of the Chari River. The northern basin may completely dry up or be seasonally inundated. Permanent or seasonal marshes ranging from 2,000 to 14,000 km² cover the northern basin of the lake and



Chad Lake, Figure 2 The main regions of the Normal Lake Chad and the location of the main sill (Great Barrier) between the southern and northern basins (Landsat MSS mosaic in January 1973. Modified from Lemoalle 1991).



Chad Lake, Figure 3 The relationship between water level and lake surface area. When the level is below ~ 280 m asl, the lake is split into two separate basins: A_s and A_n are the lake areas in the southern and northern basins, respectively. (From Bader et al., 2011).

parts of its southern basin and archipelago (Leblanc et al., 2007; Leblanc et al., 2011). This Small Lake Chad occurs when the annual discharge from the Chari River is below $34 \text{ km}^3/\text{year}$. It has been observed for short periods around 1905–1907, 1915, 1940, and since 1973. The northern basin of the lake receives no water when the annual Chari River discharge is less than 15 km^3 (Table 1).

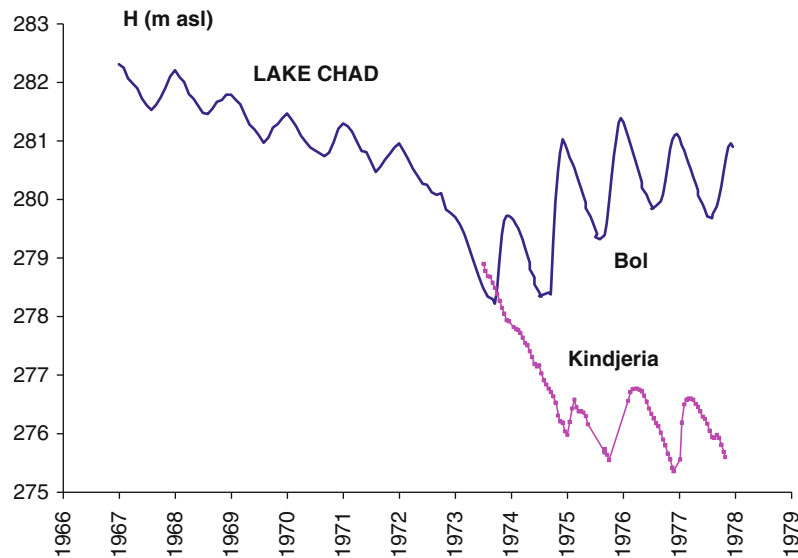
From 1957 to 2008, the lake has been in a Small state for 69% of the time and in a Normal or Large state for 31% of the time (Bader et al., 2011).

Hydrological functioning and water balance

Except during Large Lake Chad periods, the lake has no surface outflow. River and rainfall inputs are offset by evaporation losses, some seepage, and by volume and area fluctuations according both to seasonal and annual variations of the inflows. As these inflows are closely associated with rainfall over the basin, the lake is highly sensitive to climate variability. In natural conditions, it is a good indicator of climate fluctuations, but it may also react rapidly to man-made changes in its water budget.

Rainfall follows the displacement of the Intertropical Convergence Zone (ITCZ), which moves northward over the active part of the basin from February to August. Since the beginning of the 1970s, the ITCZ has not been moving as far north as before; hence, a lower rainfall over the basin.

A period of above average rainfall from 1950 to 1967 over the West African Sahel was followed by below average rainy seasons after 1970, with a succession of harmful droughts that peaked in 1972, 1973, and 1984 (L'Hôte et al., 2002; Figure 5). Over the Chari-Logone Basin, annual rainfall has decreased by about 150 mm from $1,095 \text{ mm/year}$ (1950–1967) to 932 mm/year (1972–2006) with a north-south displacement of the rainfall gradient of 150 km (Climatic Research Unit, 2003). A $\pm 10\%$ change in mean annual rainfall over the basin results in



Chad Lake, Figure 4 The water level in the two main regions of Lake Chad during the transition from Normal to Small lake. During a Small Chad state, at least two different water levels are needed to describe the lake. The locations of the gauges are given in [Figure 2](#).

Chad Lake, Table 1 The main characteristics of the different states of Lake Chad

Lake Chad	Small	Normal	Large
Chari River discharge (km ³ /year)	10–34	40	45
Water level (m asl)	Several levels	280–282	>282.3
Number of water bodies	several	one	one
Total lake area (km ²)	2,000–14,000	15,000–19,000	20,000–25,000
North basin inundated area (km ²)	0–8,000	9,000	10,000
Landscape	Marshes	Dune islands	Open waters
Aquatic vegetation	+++	++	+

a $\pm 30\%$ change in the annual discharge of the Chari River, the main tributary to the lake, which has also been lowered as follows (data from Direction des Ressources en Eau et de la Météorologie, DREM, Chad) ([Figure 6](#)):

- Period 1960–1969 – 41.0 km³
- Period 1970–1979 – 31.1 km³
- Period 1980–1989 – 16.6 km³
- Period 1990–1999 – 20.4 km³
- Period 2000–2006 – 22.0 km³

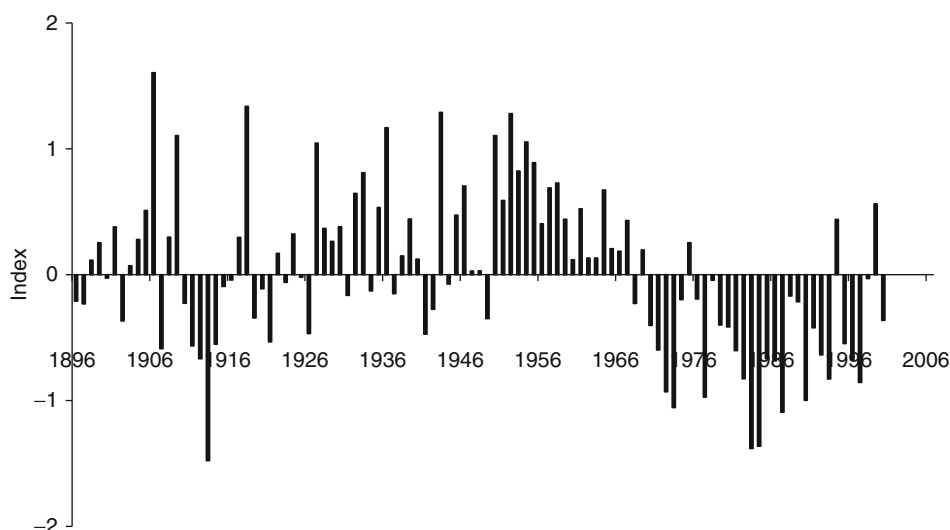
This decrease in the discharge of the Chari River is the main reason for the decline in Lake Chad water levels and the shrinking of surface area from a Normal to a Small lake.

The water budget of Lake Chad has been studied by a number of authors (see Olivry et al., 1996). Mean values for the period 1954–1969 of Normal Lake Chad are given in [Table 2](#). The main input to the lake is the seasonal discharge of the Chari River (41.7 km³/year or 82.3% of total inputs), supplemented by direct rainfall (14% of total inputs) and inflow from the other small tributaries, El Beid and Komadugu Yobe (1.43 and 0.49 km³/year, respectively, or 3.6% of total inputs). The losses result mainly from evaporation (95.5%) and seepage out of the lake (4.5%). The seepage may, however, change in direction, seasonally or from year to year, according to the trend in the change of the water level.

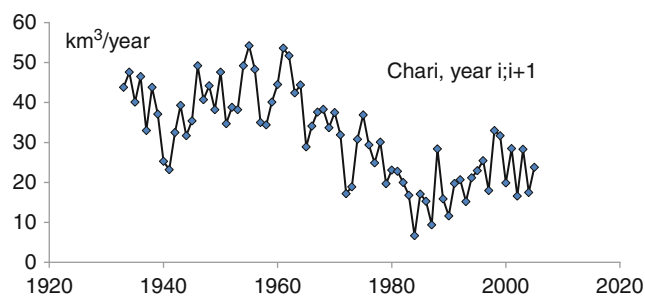
The hydrology of the Small lake is controlled by the Great Barrier, the main sill separating the two main basins ([Figure 2](#)). Its altitude is close to 279.3 m, but it is covered with dense vegetation acting as a break to the circulation of water (the Great Barrier extends more than 40 km between the two basins). The water from the Chari River feeds the southern basin and overflows over the Great barrier only when the flood is sufficient.

Starting from the seasonal low level in July or August in the southern pool, an increase in level occurs with the input of the flood from the Chari River until a level of 279.5–280 m asl is reached in December. If this level is reached, some overflow occurs toward the northern basin of the lake through the Great Barrier. An annual discharge of the Chari River exceeding about 15 km³/year is needed for this overflow to occur. The water budget of the Small Chad is quite complicated because of the separate behavior of the different basins. A hydrological model has been developed to simulate the water level and extent in these basins (Bader et al., 2011).

While the annual cycle in the southern basin during a Small Chad period is fairly similar from year to year, it



Chad Lake, Figure 5 Time series from 1896 to 2000 of a normalized rainfall anomaly index over the West African Sahel (mean value computed for 1921–2000). (From L'Hôte et al., 2002).



Chad Lake, Figure 6 Total annual discharge of the Chari River at N'Djamena (a hydrological year os from May year i to April year $i + 1$). (Data from Olivry et al. (1996) and DREM (Tchad)).

Chad Lake, Table 2 Mean values for the components of the water budget of a Normal Lake Chad (1954–1969). Values expressed as water height (mm/year) over the lake surface area (From Vuillaume, 1981)

Component	Unit	Normal Lake Chad
River inputs	mm/year	+1946
Direct rainfall	mm/year	+329
Evaporation	mm/year	−2170
Net seepage	mm/year	−102

is highly variable in the northern basin. The lake has decreased in level and area between 1965 and 1973. The process continued during 1973–1976 when the lake split into different water bodies and with the first total desiccation of the northern basin. Since 1976, Lake Chad has been in a new equilibrium of Small state (Figure 7). Contrary to news reports in the press or on the web (e.g., NASA, 2003), Lake Chad is, at the time of writing (2010), neither shrinking,

disappearing nor dying. It is a Small Lake Chad, as it has been several times in the past prior to recovering Normal or Large Lake Chad water levels.

Water chemistry

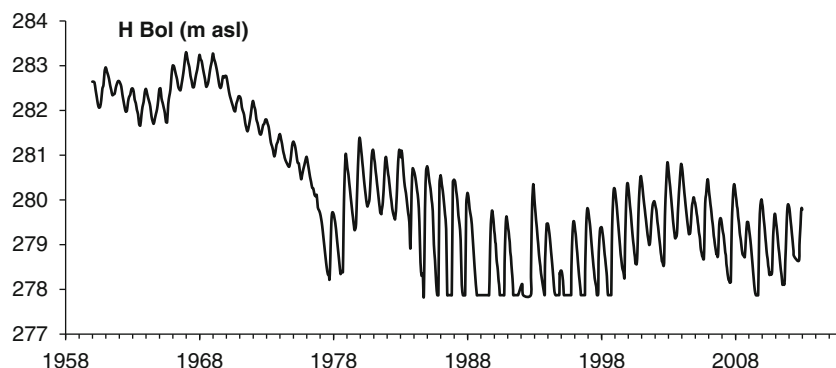
Contrary to most closed lakes in a semiarid climate, the lake water remains relatively fresh. In the Normal Lake Chad state, the water electrical conductivity is about 60 $\mu\text{S}/\text{cm}$ (TDS about 40 mg/L) at the delta of the Chari River and increases as the water progresses into the lake to the east and north. It is usually about 120 $\mu\text{S}/\text{cm}$ (TDS = 80 mg/L) at Bol and reaches 1, 200 $\mu\text{S}/\text{cm}$ (TDS about 900 mg/L) around N'Guigmi (see Figure 2). This low salinity has been explained by the combination of two processes: (1) in the water, the cations are mainly involved in chemical equilibria with precipitation of carbonates (Ca and Mg), adsorption on suspended clay particles, and possible neoformation of clay, (Carmouze, 1983), and (2) some of the most concentrated water, close to the lake shores, is exported by seepage. A small volume of seepage water thus exports a large quantity of salt which is collected as natron (sodium carbonate/bicarbonate) further inland in the small inter dune depressions.

The processes acting during the Small Lake Chad state have been less studied, but the increased CO_2 partial pressure associated with the vegetation does not allow for the same Ca and Mg precipitation.

In the open water areas, Lake Chad is polymictic, with usually a nycthemeral cycle.

Flora and fauna

The aquatic vegetation comprises mainly *Cyperus papyrus*, *Phragmites australis*, *Typha australis*, the tall leguminous *Aeschynomene elaphroxylon*, *Echinochloa sp.*, and other smaller plants such as *Ipomea spp.*



Chad Lake, Figure 7 The water level as monitored at the Bol gauge (Data from ORSTOM and DREM). Since March 1973, the Lake has split into basins of differing water levels and cannot be described by a single water level. The level from March 1979 to May 1984 has been calculated from Kirinowa levels using a correlation between the two stations.

The submersed vegetation comprises mostly *Potamogeton* and *Ceratophyllum* and does not cover large areas. Up until now, water hyacinth (*Eichhornia crassipes*) has not been present in the lake. Large quantities of *Pistia stratiotes*, *C. papyrus*, and *A. elaphroxylon* are found in the southern basin of the Normal lake but not in its northern basin, maybe because of the higher water salinity (Iltis and Lemoalle, 1983).

The distribution of these species is highly dependent on the changes in water level. In the first half of 1973, the riparian band of vegetation almost disappeared when the water level receded, but later covered most of the southern basin after the first rains in the same year. The northern basin became completely devoid of vegetation when it dried up in 1975. Later, a very dense forest of *Prosopis juliflora* rapidly covered all of its central part in the 1980s while the basin was dry. When the northern basin became inundated again, most of these trees died, and the usual aquatic vegetation developed over large areas.

The fish community in the lake is primarily riverine. It is dependent on the hydrologic conditions in the floodplains of the lower Chari, Logone and Komadugu Yobe Rivers, together with the lake proper. Many of the fish migrate for reproduction either within the lake itself or from the lake to the river system. A total of 127 fish species belonging to 27 families have been recorded in the lake, many being shared with the Nile, Niger, and Senegal Basins (Lévêque and Paugy, 1999). There are no endemic fish species to the basin.

In the large marshes of the Small Lake Chad, and especially in the northern basin, only the few species that can sustain the frequent lack of oxygen in the water remain: *Heterotis niloticus*, some tilapia, and *Clarias spp.* make the main commercial catch under these conditions.

Lake Chad and the wetlands in its basin are a main feature for migratory Palearctic and Afrotropical birds. Some 70 species make stopovers each year, including numerous garganey (*Anas querquedula*), pintail (*A. acuta*), and the ruff (*Philomachus pugnax*). Other numerically

important species include grey and purple herons, large flocks of crested cranes, the black winged stilt (*Himantopus himantopus*), and the glossy ibis. Pelicans (*Pelecanus onocrotatus*) and shags (*Phalacrocorax africanus*) may be seen in numbers in the delta of the Chari River and in the southern basin. Caspian and gull-billed terns (*Sterna tschegrava* and *S. nilotica*) are mainly fish eaters, while the whiskered and white-winged black terns (*S. hybrida* and *S. leucoptera*) have a mixed diet of fish and insects. The large emergence of chironomids or Mayflies often leads to considerable aggregations of white-winged black terns.

A few hippopotamuses (*H. amphibius*) may be seen near the Chari River delta, but in much smaller numbers than before the 1973 drought when many died because of lack of food.

The Nile monitor (*Varanus niloticus*) has benefited from the development of the marshes during the Small Lake Chad. It is quite commonly seen but subject to a heavy toll for its skin which is exported.

Under the auspices of the Lake Chad Basin Commission, Lake Chad is now registered in the Ramsar Convention for the protection of the aquatic habitat (Ramsar, 2010).

The use of natural resources

Rain-fed agriculture and livestock are the main food-producing activities in the semiarid African Sahel. A water body in such an agroclimatic region is very attractive for the surrounding populations, especially during drought periods. Since the 1973 and 1984 droughts, a large population has gathered around the lake for recession cultivation on the rich lake sediments, livestock keeping, and fishing (Kolawole, 1988).

When the Chari River flood is sufficient to inundate a large part of the northern basin of the lake, the resource availability of a "Small Lake Chad" is at its maximum in both basins and probably larger than during the Normal lake state. But the rainfall variability is such that, in some years, the river flood is insufficient to feed the northern basin of the lake which remains dry. The population in

the northern part of the lake then has to move to find their living, while the resources in the southern basin remain stable.

The heads of State of the Lake Chad Basin have thus given mandate to the Lake Chad Basin Commission to study the feasibility of a water transfer from the Ubangui River in the Congo/Zaire Basin, which would allow for more sustainable water availability in Lake Chad and for the surrounding large irrigation projects. A feasibility study has been launched in 2009.

Irrigation

The South Chad Irrigation Project (67,000 ha) and the Baga Polder Project (20,000 ha), on the Nigerian shore of the lake, were inaugurated respectively in 1979 and 1982. Their full operation would have needed 2.5 km³ of water per year, but the lake recession did not allow for the irrigation of more than 7,000 ha in the first years of operation before a complete halt (Thambyahpillay, 1983; Hollis, 1990).

Many of the reservoirs and irrigated areas (Maga dam in Cameroon, polders in Lake Chad, and reservoirs on the Komadudgu Yobe system in Nigeria) use some water which would naturally feed floodplains, where most of the water is lost through evaporation. Although this is detrimental to the floodplains ecology and their natural resources, the net water abstraction at the basin scale remains limited.

Currently, and with the available data, it is estimated that less than 200 Mm³ are abstracted annually from the Chari-Logone system upstream of N'Djamena where discharge is measured (Rép. du Tchad-PNUD, 2003). The gross water uptake in the lake for the polders irrigation scheme is 75 Mm³, but this is less than what would have evaporated from the lake surface had they not been implemented.

The net uptake for irrigation in the Lake Chad Basin, including the reservoirs on the Komadugu Yobe Basin, therefore amounts to approximately 200–300 Mm³/year. This value is much lower than previous estimates and does not substantially contribute to the present low water levels of the lake as reported elsewhere (Coe and Foley, 2001).

Contrary to the Aral Sea, the Small Lake Chad status largely results from the change in rainfall over the basin as explained above.

Threats and priorities

The models presently available on global climate change do not allow for reliable estimates of trends in the rainfall over the Lake Chad Basin during the coming decades. It is thus not possible to predict whether the natural Chari River discharge will decrease or increase as a result of climate change. Future human development in the basin may increase water abstraction through new or rehabilitated irrigated schemes around the lake or along the Chari and Logone Rivers.

It is not appropriate to say that Lake Chad is presently dying. The lake hydrology and landscapes have completely changed in 1972–1973 with the shift from

a “Normal” to a “Small” Lake Chad. But since then, the lake status has remained fairly stable, especially in the southern basin.

With the increasing population, a future reduction of the rainfall would put an unsustainable pressure on the natural resources of the basin, of Lake Chad itself, and its associated floodplains and surroundings. It is thus necessary to further improve our understanding and monitoring of surface and groundwater resources availability so that food supply and ecosystem services are guaranteed and become less vulnerable to rainfall variability.

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Cross-references

Africa, Lakes Review
 Aral Sea
 Climate Change Effects on Lakes
 Thermal Regime of Lakes
 Water Balance of Lakes

CHILIKA LAKE

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Introduction

Geological evidences indicate that the Chilika Lake was part of the Bay of Bengal during the later stages of the Pleistocene period (Pascoe, 1964). Abrupt changes in the morphology of the coast along north of the lake; strong winds shifting sand to the shore; longshore drift (littoral

drift) and the presence or absence of strong river and tidal currents in different areas are the reasons attributed to the growth of the spit. A 60-km (37 miles)-long barrier beach called Rajhansa, formed by northerly currents in the Bay of Bengal, resulted in the formation of this shallow lake and forms its eastern side. It is a shallow brackish-water inshore lake, connected to the Bay of Bengal through a narrow mouth. Chilika Lake is bordered between the sea and mountains. Formation of a barrier spit near Palur due to littoral drift and creation of a sand bar along the eastern shore have transformed the lake gradually to a shallow lagoon. Presently, the sea is connected with the lake near Satapada through a number of shoals, sand spits, sand bars, openings of shallow depth, and a narrow channel. The presence of these features considerably reduces tidal flow in and out of the lake. In the past, discharge of sediment by the tributaries of the Mahanadi River made the lake shallower, and subsequently, the lake was separated from the sea after the formation of the spit (Krishnan, 1968). The lake is continuously becoming shallow; sandbanks and a number of islands are visible just above the surface because of the discharge of silt and sediment by the rivers Daya, Bhargavi, Makra, and Nuna. About 1.6 million metric tons per year of sediment is deposited in Chilika Lake by rivers and several streams. Some of the rivers are tributaries of the Mahanadi River, and others are streams joining the lake. Water level in the lake fluctuates seasonally and during high and low tides. Similarly, maximum area of the lake experiences submergence and emergence every year.

Geography and topography

Chilika (19° 28'–19° 54' N; 85° 06'–85° 35' E), the largest subelliptical brackish-water lagoon in Asia (Figure 1) and one of the largest tropical lagoons in the world, has been marked as Category I of the marine protected areas and designated as a Ramsar site on the Ramsar Convention of Wetlands in 1981. The western and southern margins of the lake are fringed by the Eastern Ghat hill range. The north shore of the lake is part of Khordha district, and the western shore is part of Ganjam district of Orissa. The shallow water body (average depth 2 m) is about 65 km in length, spreading from northeast to southwest parallel to the coastline with a variable breadth reaching 20.1 km. The lagoon spreads over an area of 950 km² during summer, which swells up to 1,165 km² during monsoon (Siddiqui and Rama Rao, 1995). The lagoon is connected with the Bay of Bengal near Satapada by means of an artificial opening made in September 2000 before which a 24-km-long narrow and curved channel running parallel to the coast was joining with the Bay of Bengal near Arakhakuda. During winter (November–January), a large portion of this lagoon remains submerged and acts as a wetland, which also serves as breeding and nesting grounds for millions of migratory bird species. High evaporation from the shallow water body during summer (April–June) and a large inflow of freshwater through



Chilika Lake, Figure 1 Chilika Lake showing the catchment area and connection to the Bay of Bengal through the new mouth.

various rivers and rivulets at the northern end of the lagoon during the monsoon (July–September) and post-monsoon (October–November) seasons significantly influence the water spread area of the lagoon (Mohanty et al., 1996). The catchment area of the lagoon is 4,406 km², in which 68% is constituted by western catchment and 32% by the Mahanadi delta. The total inflow of freshwater has been estimated at 14, 331 million cubic kilometers per year (Panigrahi et al., 2009). The three distributaries of Mahanadi River, namely, Daya, Bhargavi, and Nuna, account for 55% of the total inflow whereas the streams/rivulets from the western catchment contribute the rest 45% (Annon, 2003). Over the years, the lake environment is under severe stress due to siltation, changes in salinity, weed infestation, aquaculture activities, decline in fish yield, loss of biodiversity, etc. A severe cyclonic storm in 1999 caused dramatic change in the biotic communities in the lake.

Floral diversity

Phytoplankton

Phytoplankton community of Chilika Lagoon consists of a mixture of marine, brackish-water, and freshwater taxa, mainly represented by four groups of algae – diatoms (Bacillariophyceae), dinoflagellates (Pyrrophyceae and Dinophyceae), blue-green algae (cyanobacteria), and

green algae (Chlorophyceae). A maximum number of 128 species of phytoplankton have been reported from the lake (Panigrahi et al., 2009). Diatoms are the dominant group and represented by 79 species (41 centrales and 38 pennales). The dinoflagellate population is represented by 13 species. Blue-green and green algae (with 9 families and 15 genera) are represented by 18 species each. Some of the recent dominant taxa of phytoplankton, including those distributed throughout the lagoon as well as those in the more freshwater-influenced northern sector and the saline-water-dominated outer channel area, are reported elsewhere (Panigrahi et al., 2009). The phytoplankton assemblages of the lagoon are dominated by diatoms, certain dinoflagellates, and blue-green algae during summer season when the salinity in most parts of the lagoon is about 17 psu. However, during the winter season, the plankton flora is mainly represented by blue-green and green algae. Phytoplankton species composition also varies spatially between seasons. In general, the outer channel area has higher species diversity than the other regions. Diatoms dominate the species composition in the entire lagoon except for the northern region. Dinoflagellates are known to occur frequently in the outer channel area and in the southern region of the lagoon. Northern and central regions had overwhelming numbers of blue-green and green algae. Patnaik (1973) had

reported that the phytoplankton assemblages in the Chilika Lagoon consisted of 54% diatoms, 44.7% blue-green algae, 0.8% dinoflagellates, and 0.6% green algae. The available literature on the lagoon before inlet opening indicates a high degree of variability in phytoplankton composition and density. Biswas (1932), Roy (1954), Patnaik (1973), Patnaik (1978), Panigrahy (1985), Raman et al. (1990), and Adhikary and Sahu (1992) reported taxon richness of 22, 33, 57, 21, 82, 97, and 28, respectively.

Macroalgae and higher plants

The northern and central part of the Chilika Lagoon is densely covered with macrophytes which have a cyclic growth. They grow luxuriantly in the late monsoon and post-monsoon periods and start decomposing in the beginning of summer, with increase in salinity (Panigrahi, 2006; Pal and Mohanty, 2002). The cyclic growth and decomposition of aquatic weeds have been significantly influencing the oxygen saturation of the lagoon water. Hence, levels of DO increase during post-monsoon period due to the photosynthetic release, and its decrease has been noticed when they start decomposing in the summer. Even though there is no rocky intertidal region on the coastline, the rocky islands of Chilika Lake provide home for luxuriant growth of some green, brown, and red algae. The most prominent among them is the agarophyte *Gracillaria verucosa* that serves as a source of agar-agar. Mitra (1946) had estimated that about 4–5 t of *Gracillaria* could be harvested per annum from this lake. The growth of seaweeds in this lake however has considerably declined due to the problem of siltation and salinity reduction in the lake water in the subsequent years.

Recent surveys revealed that an overall 726 species of flowering plants belonging to 496 genera and 120 families are present in and around the Chilika Lake. This represents about one-fourth of the vascular plant species of the Orissa state. Fabaceae is the most dominant plant family followed by Poaceae and Cyperaceae. Certain species were found to be characteristic to specific islands. The flora is predominantly of aquatic and sub-aquatic plants. The species reported are from the families Leguminosae, Poaceae, and Cyperaceae and endemic *Cassipourea ceylanica* along with five species of seagrass. Wild plants of horticultural importance and interesting plant groups such as insectivorous plants, epiphytes, parasites, and lithophytes are also found in the lake environment. Mangrove associates, such as *Aegiceras corniculatus*, *Excoecaria agalloch*, *Salvadora persica*, *Pongamia pinnata*, *Colubrina asiatica*, *Capparis roxburghii*, *Macrotyloma ciliatum*, and many others, are found in abundance.

Faunal diversity

The lake harbors a rich faunal diversity. In total, 323 fish species, 24 mammals, and 37 species of reptiles and amphibians have been reported. The rare and threatened animal species identified in the lake milieu are green sea turtle (endangered), dugong (vulnerable), Irrawaddy

dolphin (vulnerable), blackbuck (near threatened), spoon-billed sandpiper (critically endangered), limbless skink, and fishing cat (endangered).

Zooplankton

Zooplankton studies in the Chilika Lake, in fact in India, started in early twentieth century by Sewell (1913) followed by Annandale and Kemp (1915). Subsequently, observations were made by Devasundaram and Roy (1954), Jhingaran (1963), and Mohanty (1975). Recent observations have shown a significant spatial and temporal variation in zooplankton species composition, population density, and relative abundance. Zooplankton density in Chilika Lagoon ranges from 1740 to 10370 individuals m^{-3} while the biomass values range from 1.72–3.30 $g\ m^{-3}$ (Naik et al. 2008). Copepods, chaetognaths, cladocerans, mysids, lucifers, euphausiids, siphonophores, and sergestids are the dominant groups observed in the lake waters. Copepods alone contribute nearly 70% of total density. The distribution of zooplankton is found to be significantly influenced by salinity variations in the lake.

Fishery

The 323 species of fishes found in the lake involve 261 fin-fish species, 28 prawns, and 34 crabs out of which 65 species breed in the lake (Chilika Development Authority, 2008). Of these, 27 fishes and two genera of prawns are freshwater species. For centuries, fisher folk evolved exclusive rights of fishing through a complex system of partitioning the fisheries of the lake, harvested the lake in a relatively sustainable fashion and developed a large range of fishing techniques, nets, and gear. Butter catfish and *Wallago attu* are the most common types of fish found in the lake. Eleven species of fish, five species of prawn, and two crab species are commercially important. The commercially important prawn species are giant tiger prawn, *Penaeus indicus* (Indian white shrimp), *Metapenaeus monoceros* (speckled shrimp), *Metapenaeus affinis* (pink prawn) and *Metapenaeus dobson* (Kadal shrimp). Mangrove crab is the most important commercial crab available in the lake. Fish landings in the lake, which fluctuated widely in the past, have recorded a remarkable recovery after the opening of the new mouth and dredging of silt-choked old mouth Magarmukh in 2000–2001. This has been attributed to better intermixing of the tidal influx from the sea and freshwater inflow from rivers. Against an all-time lowest landing of fish and prawn of 1,269 t (1,399 short tons) in 1995–1996, the all-time high is reported to be 11,878 t (13,093 short tons) during 2001–2002, resulting in an estimated per capita income for the fisher folk of Rs 19,575 (about US\$392) during that year (Chilika Development Authority, 2008).

Dolphins

The Irrawaddy dolphin present in the Satapada area of the Chilika Lake has been attracting tourists not only from India but also from all over the world. The Irrawaddy

dolphin (*Orcaella brevirostris*) is the flagship species of Chilika Lake. Chilika is the only home to Irrawaddy dolphins in India and one of only two lagoons in the world that are home to this species (Sutaria, 2007). It is classified as critically endangered in five of the six other places it is known to live (Cetacean Specialist Group, 1996). A small population of bottlenose dolphins also migrates into the lagoon from the sea. Chilika fishermen say that when Irrawaddy dolphins and bottlenose dolphins meet in the outer channel, the former get frightened and are forced to return toward the lake. Some Irrawaddy dolphins used to be sighted only along the inlet channel and in a limited portion of the central sector of the lake before the opening of the new mouth. After the opening of the new mouth at Satapada in 2000, they are now well distributed in the central and the southern sector of the lake. The number of dolphins sighted has varied from 50 to 170. A 2006 census counted 131 dolphins, and the 2007 census revealed 138 dolphins. Out of the 138 dolphins, 115 were adults, 17 adolescents, and six calves. Sixty adults were spotted in the outer channel followed by 32 in the central sector and 23 in the southern sector (Das, 2008).

Birds

Chilika Lagoon receives thousands of avian guests coming from faraway places like Siberia during winter months. The presence of such wonderful birds adds to the bounty of the amazing coastal ecosystems along Orissa, for which millions of tourists come here to witness this unique phenomenon of nature. Chilika Lake is the largest wintering ground for migratory birds on the Indian sub-continent. It is one of the hotspots of biodiversity in the country. Some species listed in the IUCN Red List of Threatened Species inhabit the lake for at least part of their life cycle. White-bellied sea eagles, graylag geese, purple moorhen, jacana, herons and flamingos, egrets, gray and purple herons, Indian roller, storks and white ibis, spoonbills, brahminy ducks, shovellers, and pintails are some of the important species found here. According to a survey, 45% of the birds are terrestrial in nature, 32% are waterfowl, and 23% are waders. The lagoon is also home to 14 types of raptors. Migratory waterfowl arrive here from as far as the Caspian Sea, Baikal Lake, and remote parts of Russia, Mongolia, Lakah, Siberia, Iran, Iraq, and Afghanistan and from the Himalayas. In 2007, nearly 840,000 birds visited the lake, out of which 198,000 were spotted in Nalbana Island. On January 5, 2008, a bird census involving 85 wildlife officials counted 900,000 birds of which 450,000 were sighted in Nalabana. Removal of invasive species of freshwater aquatic plants, especially water hyacinth, due to restoration of salinity, is a contributing factor for the recent increasing attraction of birds to the lake.

Environmental status

The lagoon has several hydrological influences. Important among them are (1) drainage from unregulated degraded catchment basin lying on the western and southern

boundaries, (2) silt-borne freshwater discharges from the distributaries of Mahanadi River, and (3) exchange of lagoon water with Bay of Bengal. Changes in the strength and nature of these hydrological connections can have drastic and potentially unexpected consequences for the lagoon. The spatial and temporal salinity gradients caused due to freshwater flow from the riverine systems and seawater intrusion under tidal influence give it the characteristics of an estuarine ecosystem.

There has also been a general increase in the pollution load from agricultural waste, aquaculture, and domestic sources from the drainage basin. The western catchment contributes an average of $\sim 536 \text{ m}^3 \text{ S}^{-1}$, and the distributaries of the Mahanadi River (Daya, Bhargavi, and Nuna rivers) contribute an average of $\sim 850 \text{ m}^3 \text{ S}^{-1}$ (Patnaik, 2002). Furthermore, the introduction of prawn culture ("gheri" or bund fishing) in 1991 led to various changes in hydrology and sediment transport processes, mainly as a result of the use of split bamboo and very fine mesh nets encircling the culture area, which prevented free sediment flow. The amount of sewage discharged to the lagoon from the capital city Bhubaneswar was observed to be ~ 550 million liters day^{-1} , along with a huge amount of untreated domestic wastewater from the 141 villages in and around the lagoon. Analysis of the capital city's wastewater indicates suspended solids concentrations of roughly 275 mg l^{-1} and an average biochemical oxygen demand of 110 mg l^{-1} (Panigrahi et al., 2009), far above the permissible limit of 20 mg l^{-1} (Orissa State Pollution Control Board, unpublished data, 1998). The siltation, reduced salinity, increased pollutant load from the catchment basin, and restricted outflow of lagoon water (to the sea) resulted in the rapid growth of invasive weed species in the northern sector and eutrophication throughout the lagoon. The lagoon is severely threatened by problems like shrinkage of area and decreased depth due to siltation, decreased salinity, macrophyte infestation, eutrophication, and loss of biodiversity. The weak circulation of the lagoon water and poor tidal influx are responsible for the reduction in salinity. These changes in the lagoon environment are a cause of concern for both the local and the national governments, and several conservation measures such as the dredging of a new mouth and public awareness campaigns have been initiated. However, the lack of true catchment basin management has led to the influx of a huge amount of suspended sediment into the lagoon, which has altered its ecology significantly. Siltation, declining salinity, and nutrient inflow have led to extensive macrophyte growth in the lagoon. Free-floating invasive species (e.g., *Azolla*, *Eichhornia*, *Nymphaea*, *Pistia*) and emerging species (e.g., *Ipomea*) have become a common sight. Among the submerged species, *Potamogeton*, *Hydrilla*, and *Najas* are common. Weed infestation increased from 20 km^2 in 1973 to 440 km^2 in 1998 and reached 523 km^2 in 2001. In 2001, emergent weeds covered 86.07 km^2 , free-floating weeds covered 110.74 km^2 , and submerged weeds covered 326.19 km^2 of the lagoon. *Paspalum vaginatum*,

Paspalidium punctatum, *Potamogeton nodosus*, and *Potamogeton pectinatus* dominated the macrophyte community. *Potamogeton* alone accounted for 78% of the invasive species (Ghosh et al., 2006). In spite of the new mouth opening, the weed infestation has not declined, but rather is in the increasing trend possibly due to nutrient enrichment. Thus, the unregulated discharge of various wastes has to be stopped in order to abrogate the weed menace.

The important rivers of this drainage system are the Kansari, the Kusumi, the Janjira, and the Tarimi rivers. The annual total surface freshwater input to the lake is estimated to be 14, 331 million cubic kilometers per year (Panigrahi et al., 2009) which is estimated to carry 1.6 million metric tons of silt into the lake. On the northeast, a channel connects the lake to the Bay of Bengal. A tropical monsoon climate prevails over the drainage basin area of the lake. The lake experiences southwest and northeast monsoons during June to September and November to December, respectively, with average annual rainfall of 1,300 mm (48.77 in.), with 72 rainy days. The maximum air temperature of 39.9°C (103.8°F) and minimum temperature of 14°C (57.2°F) have been recorded. The wind speed varies from 5.3 to 16 m (17 to 52 ft)/s with southerly and southwesterly direction due to the influence of the southwest monsoon and from northerly and northeasterly direction due to the influence of northeast monsoon.

Water quality

The lake is broadly divided into four zones on the basis of water salinity values, namely the southern, central, northern, and outer channels. Tidal influx of seawater during monsoon is arrested by the strong influx of a large amount of freshwater from the northern and central zones. Brackish-water conditions in the southern zone, even during monsoon, prevail due to low water exchange. Salinity in the southern zone decreases during the post-monsoon period and in winter as northern winds facilitate mixing of water with the rest of the lake. During the summer, intrusion of salt water from the outer channel into the lake increases since water level of the lake is at its lowest level. A general increase in salinity of the central and northern zones occurs due to wind-induced mixing by the predominant southern winds, and salinity in the southern zone does not change appreciably. The lake at Daya River mouth behaves like a freshwater lake, and it changes to hyper-saline level of 42 ppt in the outlet channel during the dry period. Lake water is alkaline with pH ranging from 7.1 to 9.6. The southern part of the lake has recorded the highest alkalinity. On a seasonal scale, the DO values show a wide range of variations with average values ranging from 7.2 to 7.9 mg l⁻¹, 8.0 to 8.3 mg l⁻¹, and 6.7 to 7.5 mg l⁻¹ in monsoon, post-monsoon, and summer, respectively. Higher values were reported during post-monsoon followed by the monsoon and summer. The northern and central sectors exhibit lower DO contents as compared to the southern sector (Panigrahi et al.,

2009). High turbidity due to strong mixing of overlying water with sediments results in a low water transparency which ranges from 9 to 155 cm. The huge quantity of silt-borne surface runoff from the catchment area significantly affects the optical property by massive addition of suspended sediments. Phosphate phosphorus (0–0.4 ppm), nitrate nitrogen (10–60 ppm), and silicates (1–8 ppm) are high in the north and northwest part of the lake where most of the rivers discharge into the lake with large amounts of silt and nutrients. The water quality parameters of the whole lagoon before the opening of the new mouth were reported by Nayak et al. (2004); at that time, the nutrient dynamics of the lagoon were heavily influenced by the proliferation of macrophytes. The phytoplankton components revealed by the chlorophyll-a concentration on an average range from 1.95 to 5.75 mg m⁻³, 2.55 to 7.58 mg m⁻³, and 3.79 to 8.33 mg m⁻³, corresponding to post-monsoon, monsoon, and summer, respectively (Panigrahi et al., 2009). Higher values are generally observed in the northern sector except in summer, whereas central sector shows higher concentrations in summer. It is observed that turbidity acts as the key factor controlling the photic property of the lagoon environment (Qasim, 1980; Nixon, 1988; Panigrahi et al., 2009) and thereby controls the phytoplankton production. Ratios of nitrogen to phosphorous in the lagoon suggest that primary production by phytoplankton is nitrogen limited (Panigrahi et al., 2009).

Sedimentation/siltation

The lagoon basin can be considered as shallow, with the highest depth of 2.5 m in the southern sector and some parts of central sector, which was recorded at 3.4 m during 1990 (Tripathy, 1995). The average depth of the lagoon has been decreasing over a period of time. This alarming reduction in the depth of the lagoon is attributed to the deposition of fine sediment particles by the influx from the unmanaged catchment basin and rivers of Mahanadi delta. During monsoon months, the depth of the water column increases due to the massive freshwater influx into the lagoon and minimal flushing of flooded water through the mouth. Thus, the exchange of water and sediment between the lagoon and the sea gets considerably affected by the choking of the outer channel and the northward shift of the inlet mouth (Chandramohan and Nayak, 1994). The shifting and blockage of the lagoon mouth are ascribed to the addition of silt from upstream catchments as well as oceanic longshore transport. The longshore sediment transport (littoral drift) along the coast of the Bay of Bengal is about 0.1 million metric tons (MT) annually, and this shifts the lagoon mouth (the opening to the sea) every year, thereby adversely affecting tidal exchange. The major silt load carried by the tributaries of the Mahanadi River system is 1.5 million MT year⁻¹, while 0.3 million MT year⁻¹ of sediment enters from the western catchment (Ghosh et al., 2006). The upstream erosion and sedimentation processes in the lagoon directly contribute to the loss of lagoon depth as well as the

blockage of the mouth. The total sediment load discharged into the lagoon has been estimated to be 1.8 million MT in 1998 (Patnaik, 1998) and went up to 2.94 million MT in 2001 (Annon, 2003). Spatial variation in sedimentation rate (mm/year) in three zones of the lake, 7.6 in the northern sector, 8.0 in central sector, and 2.8 in the southern sector, has been reported. The sedimentation rate along with the porosity and water content of the sediment cores indicates that the lake has different deposition zones, with comparatively higher sedimentation rate in northern and central sectors and a slow rate in the southern sector.

Distribution of sediment and sedimentary structures

The sediment dispersal patterns and the sedimentary structures in the Chilika are primarily controlled by hydrographic and hydrodynamic conditions prevailing in different areas together with the availability of sediments. In the inlets of the lagoon where current velocity is rather high, sandy sediments predominate, and current ripples, ripple laminations, and medium- to small-scale trough and lenticular cross-beds are pronounced sedimentary structures. By contrast, in areas farther off from the inlets with lower flow velocity, the sediments are silty to muddy. Major part of the lagoon bottom shows an admixture of biogenic debris and mud with occasional intercalated lenses of sand.

Aeolian sand predominates in the sea-facing dunes. The linear barrier bar or spit is chiefly composed of clean sand particularly at its beach faces. The lagoon bottom sediments are parallel laminated and often disturbed by bioturbation structures. Penecontemporaneous deformation structures characterize the layers at greater depths.

Macrobenthic communities play a significant role in producing surface bioturbational structures. Microbial mat layers with curled mud cracks are common in subaerial marginal parts.

Degradation of lake environment and restoration activities

The lagoon was severely threatened by problems like shrinkage of water spread and decrease in depth due to siltation, fall in salinity, macrophyte infestation, eutrophication, and loss of biodiversity when the old mouth was closed due to longshore sediment transport. The weak circulation of lagoon water and poor tidal influx further complicated the conditions leading to deterioration of the environment. Considering the threats faced by the lake, the National Wetlands, Mangroves and Coral Reefs Committee of the Ministry of Environment and Forests, Government of India, and the state government identified the lake as a priority site for conservation and management. Thus, in 1992, the Government of Orissa, concerned by the degradation of the lake's ecosystem and cognizant of significant numbers of people who were dependent upon the lake's resources, set up the Chilika Development Authority (CDA). It was set up for

restoration and overall development of the lake under the Indian Societies Registration Act as a parastatal body under the administrative jurisdiction of the Forest and Environment Department, with the following objective:

- To protect the lake ecosystem with all its genetic diversity
- To formulate the management plan for integrated resource management and wise use of the lake's resources by the community depending on it
- To execute multidimensional and multidisciplinary developmental activities either by itself or through other agencies
- To collaborate with various national and international institutions for the development of the lake

The most effective ameliorative action was the hydrological intervention by opening the new lake mouth and channel to the sea through the barrier beach at Satapada. This improved the spatial and temporal salinity gradients of the lake to maintain the unique characteristics of an estuarine ecosystem. This intervention was undertaken after detailed scientific studies, including three-dimensional mathematical modeling and hydraulics studies on a model prototype, by the Central Water and Power Research Station, Pune and National Institute of Oceanography, Goa. In September 2000, the desiltation of the channel connecting the lake to the sea and opening of a new mouth to restore the natural flows of water and salinity levels were carried out. These actions resulted in a notable increase in the lake's fish yield and a reduction of freshwater weeds. The new mouth reduced the length of the outflow channel by 18 km. Opening of the new mouth provided a favorable increased salinity regime throughout the lake with less fluctuations and improved water clarity. The other restoration activities by CDA involved (1) catchment management in a participatory micro-watershed management in a whole ecosystem approach, (2) protection of bird habitat and of bird species, (3) economic incentives to the local population to stop poaching of birds, (4) measures to improve the socioeconomic conditions, such as training programs to develop ecotourism, (5) provision of solar streetlight systems to island villages, (6) development of a ferry service for isolated villages, and (7) construction of fish landing facilities for fisher folk, as well as educational and environmental awareness activities.

A significant change in water quality was experienced after the opening of the new mouth. The mean seasonal values of different parameters were reported to have shown significant changes in the lagoon environment during the post mouth opening period. The mean depth of the water column of the lagoon during 2001–2003 was lower than that of 1998–2000. This is attributed to better flushing of water and sediment from the lagoon to the sea, as facilitated by the new opening. A remarkable increase in salinity has been noticed during 2001–2003, as compared to before the opening of the new mouth (1998–2000). The

average salinity of the lagoon has undergone a series of visible changes, such as 27–33 ppt in 1957, 13–20 ppt in 1960–1961, 9.4–11.8 ppt in 1961–1964, and 1.38–6.3 ppt during 1995 (Sarkar, 1977; Raman et al., 1990; Siddiqui and Rama Rao, 1995; Panigrahi 2006). The salinity concentration of the lagoon reached 21.5 psu on average, with individual values varying between 0.5 and 31.6 psu during post mouth opening period, 2003 (Panigrahi et al., 2009). The change in salinity had largely occurred due to the exchange of seawater and lagoon water through the newly opened inlet channel. No significant change in pH was observed after the new mouth has been opened. The average total suspended solid (TSS) values of the lagoon during the post mouth opening period remained much below than those seen before the mouth was opened (1998–2000). This indicates a better flushing out of suspended sediments from the lagoon to the sea. The chlorophyll-a concentration lowered in the lagoon; phosphorus nutrients (PO_4^{3-} -P and TP) were enriched and nitrogenous nutrients decreased in concentration following the opening of the new inlet. A significant decrease in freshwater weed proliferation has been reported since the opening of the inlet (Patnaik, 2005). In 2002, Chilika was taken out of the Montreux Record, in light of the improved conditions of the lake. Chilika Lake is the first Ramsar site in Asia to be removed from the Montreux record.

Tourism

Chilika Lake is a popular destination for the ecotourism. The Nalabana Island is the popular bird sanctuary, known as the Chilika Wildlife Sanctuary. Due to a wide range of species of birds, Chilika Lake acts as a popular birding site. It is also quite popular for fishing and angling, and visitors have the opportunity to take the boat cruise around the lake. Visiting the sightseeing destinations around the lake can be an enchanting experience. Thousands of pilgrims flock to visit the Kalijai Island every year to pay homage to the Goddess Kalijai. Satapada where the famous Chilika dolphins are generally seen in a relatively large number serves as the most important tourist spot of the lake.

Conservation and management

- Over a million migratory waterfowl and shorebirds winter here.
- Over 400 vertebrate species have been recorded.
- As an estuarine lagoon, it supports a unique assemblage of marine, brackish, and freshwater species.
- Several rare and endangered species are found in the region.
- The lake supports fisheries that are the lifeline of the community.
- The lake is of great value in preserving genetic diversity.
- There is an increase in weeds and aquaculture activities.

Over the years, the ecosystem of the lake encountered several problems and threats such as:

- Siltation due to littoral drift and sediments from the inland river systems
- Shrinkage of water surface area
- Choking of the inlet channel as well as shifting of the mouth connecting to the sea
- Decrease in salinity and fishery resources
- Proliferation of freshwater invasive species
- An overall loss of biodiversity with decline in productivity adversely affecting the livelihood of the community that depended on it
- Fights between fishermen and non-fishermen communities about fishing rights in the lake and consequent court cases

Conclusion

Anthropogenic activities related to the processes influencing the quality of water of Chilika Lagoon are agricultural drainage, river runoff containing urban sewage, and drainage from the agro-based industries (prawn-processing units). These types of inputs altered the ecology of the lagoon severely and also affected the overall biotic community of the ecosystem. Accumulation of a huge amount of silt gradually decreased the depth of the lagoon and helped the intensification of macrophyte growth. The role of freshwater influx has been critical in bringing salinity changes and cyclic growth and decomposition of macrophytes in the lagoon. A significant improvement in overall quality of the lake environment has been observed after the new mouth opening. However, to restore the ecological stability and economic vitality of the lagoon, an integrated approach to ensure all round development including social, economic, and institutional development is required. The approach to be followed should be catchment area treatment, water management, biodiversity conservation, and sustainable resources development and management.

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Cross-references

Coastal Lagoons
 Indian Lakes
 Lake Restoration
 Sedimentation Processes in Lakes
 Wetlands

CHINESE LAKES

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Introduction

Compared to many lake-rich countries, lakes in China play a less important role compared to other water bodies. In a nationwide water resources assessment project in 1992, Department of Hydrology, Ministry of Water Resource (MWR) of China has concluded that the number of lakes with an area over 1 km² is around 2,300, and the total area of all the lakes amounts to 71,000 km², which is about 0.8% of the total territory of the country. The total storage capacity of all lakes reaches 708 billion cubic meters, which is about 11% of the annual precipitation volume. Besides, there are over 86,000 reservoirs with a total storage capacity of 413 billion cubic meters (Department of Hydrology, MWR China, 1992). Most of the freshwater lakes and reservoirs are exploited and used for multipurpose usage including drinking water, industrial and agricultural production, as well as aquaculture. The assessment also compiled all data from China and divided the nations lakes into five major districts based on their geographical distributions shown in Table 1.

In a more recent investigation carried out jointly by MWR and Nanjing Geographic & Lake Research Institute, a more detailed classification has been implemented and the resulting codes are considered as the national standard for lake classification (MWR and Nanjing Geographic and Lake Research Institute, 1998). The classification report concluded that the total number of lakes (>1 km²) were 2,928 with a total lake area of 93,956 km², much more than that of the 1992 report. The summary of the 1998 report is displayed in Table 2. However, a recent report by Ma et al. (2010) concluded that as many as 243 lakes over 1 km² in size vanished in China during the last 50 years.

Some major lakes in China are described and presented below. The numbers in front of the lake names are marked in the sketch map in Figure 1. The shaded areas (red) in the figure represent other major lakes.

Poyang Lake① (E116°18', N29°05')

Poyang Lake is the largest freshwater lake in China and also the most economically important lake. The area of the lake is 3,960 km² with a storage capacity of 25.9

billion cubic meters. Poyang Lake lies in the grassland, south to Yangtze River and north to Jiangxi Province. Hydraulically, the lake connects to Yangtze River through a neck formed waterway near Duchang. The part south to Duchang is broad and is the main part of the lake. The water area of lake is 161,000 km², receiving flows from the five main rivers in Jiangxi Province, namely, Ganhe River, Fuhe River, Xinhe River, Raohe River, and Xiuhe River. The outlet sluicing water into Yangtze River is at Hukou. The average water volume per annual is about 150 billion cubic meters. Perhaps the most hydrological function of the lake is its regulating volume during flooding season. The regulating capacity of the lake is estimated to take up 20% of the Yangtze River runoff on an annual basis. For instance, in the 1954 flood the lake stored as much as 230 billion cubic meters water, playing a key role in safeguarding the downstream flooding protection.

Dongting Lake② (E112°29', N29°10')

Dongting Lake is the second largest lake of China. It lies in the south bank of Yangtze River and stands in the north part of Hunan Province. The lake extends across Hubei and Hunan with an area of about 2,700–2,800 km², and the storage capacity is 17.8 billion cubic meters. The area of the lake varies significantly due to the water balance and the human impact. There is a tendency of shrinking lake area in recent decades. Besides its intensive fishery and aquaculture-based economy, it has similar hydrological functions as Poyang Lake in retaining flooding water from Yangtze. Extensive human activities in the lake area have made it more vulnerable to environmental changes such as drought and flash flood.

Taihu Lake③ (E120°15', N31°15')

Taihu Lake lies in the bottomland in the south of Yangtze River Delta. It connects closely to the short hills of Tianmu Mountain Chain in the west, and is about 100 km far from the East China Sea. The lake extends across Jiangsu Province and Zhejiang Province but is administrated by Jiangsu Province. Taihu Lake is the third largest freshwater lake in China with an area of 2,292 km² but the water depth is in general less than 2 m. Taihu Lake is one of the most important water supply sources for the surrounding regions including Shanghai. With a population density of nearly 1,000/km² and rapid economic development during recent decades, the water quality deterioration and environmental degradation in the lake area are becoming urgent issues.

Hongze Lake④ (E118°31', N33°23')

Hongze Lake is the fourth largest freshwater lake in China with an area of 1,800 km². It lies in the northwest part of Jiangsu Province and stands in the lower reaches of Huaihe River. The swan-like form of the lake has changed many times in history and expanded in size due to the change of the Yellow River and Huaihe courses.

Chinese Lakes, Table 1 Distribution of lake area and storage in China

Lake district	Lake surface area (km ²)	Percentage to country's lake acreage (%)	Lake storage (10 ⁹ m ³)	Freshwater storage (10 ⁹ m ³)	Percentage to total freshwater storage (%)
Qinghai-Tibet plateau	36,889	51.4	518.2	103.5	45.8
Eastern plains	21,641	30.2	71.1	71.1	31.5
Mongolia-Xinjiang plateau	9,411	13.1	69.7	2.35	1.0
Northeastern plains and mountains	2,366	3.3	19.0	18.85	8.3
Yunnan-Guizhou plateau	1,108	1.5	28.8	28.8	12.7
Others	372	0.5	2.0	1.5	0.7
Total	71,787	100	708.8	226.1	100

From: Department of Hydrology, MWR China, 1992

Chinese Lakes, Table 2 Code and distribution of lake area in China (1998)

Code	Basin (region)	km ² > 1,000	km ² 500–1,000	km ² 100–500	km ² 10–100	km ² 1–10	Subtotal (Nr)	Total area km ²
A	Heilongjiang	2	1	5	25	109	142	6,057.3
B	Liao River				2		2	83.1
C	Hai River			1	3	1	5	571.6
D	Yellow River		2	2	9	16	29	1,849.7
E	Huai River	2	1	6	25	46	80	6,233.7
F	Yangtze River	3	1	16	110	583	713	17,426.6
G	Zhejiang and Taiwan				2	14	16	60.2
H	Pearl River			1	5	2	8	344.1
J	Lancang and Nu River			2	3	26	31	559.2
K	Yaluzangpu River				7	42	49	318.3
L	Pengqu and Heng River				2	7	9	36.3
M	Shiquan and Indus River				1	9	10	40.1
N	Irtys and Ob River				1	3	4	61.0
P	Dzungaria inland		3	3	11	43	60	3,008
Q	Tarim inland	1	1	6	15	70	93	8,286.2
R	Chaidamu inland	3	2	10	23	25	63	14,519.3
S	Hoh Xil and Kumukuli inland		2	9	33	124	168	4,950
T	Northern Tibet	2	4	37	185	408	636	23,034.7
U	Southern Tibet		1	2	12	21	36	1,713.3
V	Ordos inland				6	85	91	429.9
W	Inner Mongolia plateau			6	32	398	436	2,827.0
X	Baicheng and Fuyu inland				25	100	125	855.7
Y	Wuyuer inland				7	65	72	312.6
Z	Other inland			1	3	46	50	379.2
	Total	13	18	107	547	2,243	2,928	93,956.2

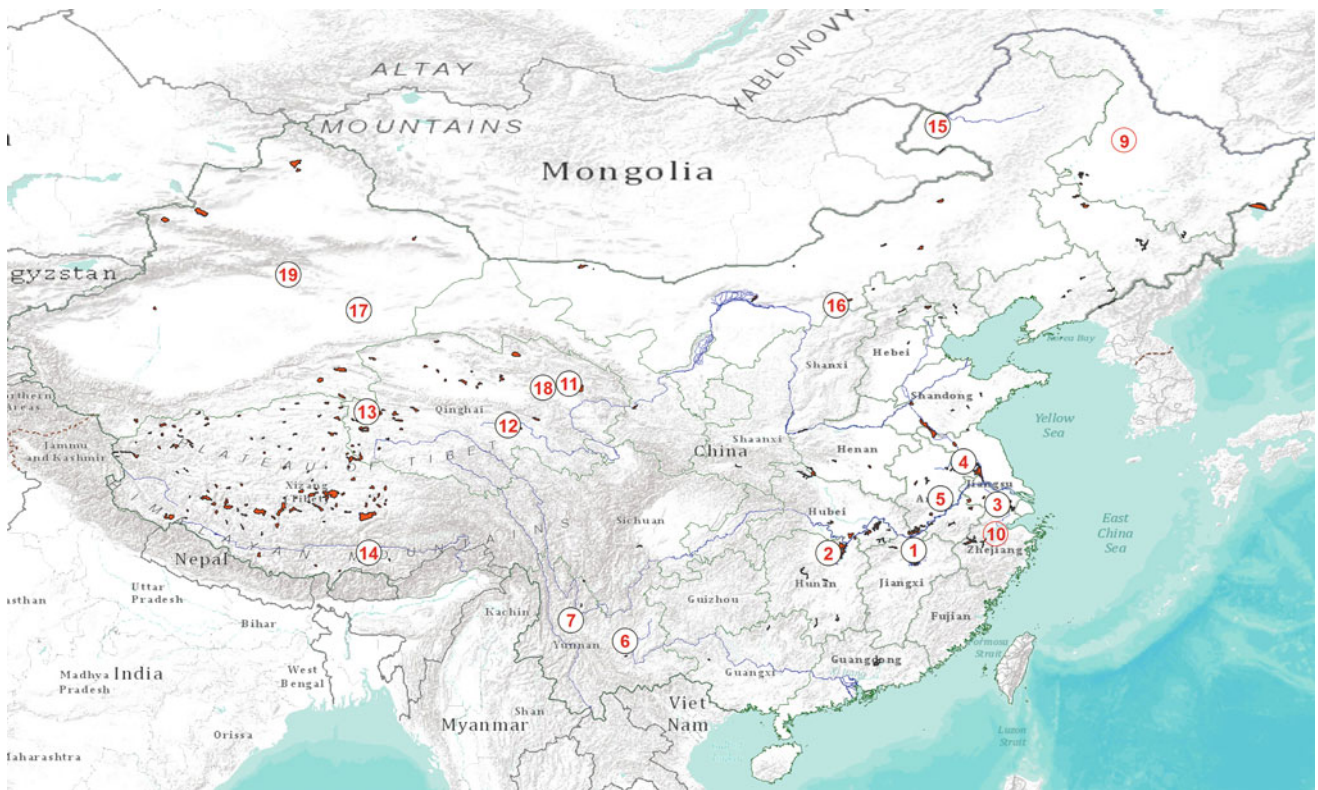
Chaohu Lake⑤ (E117°30', N31°34')

With an area of 753 km² and storage capacity of 1.8 billion cubic meters, Chaohu Lake is traditionally recognized as the fifth largest freshwater lake in China. It is the largest lake in Anhui and lies in the middle of the Province. The lake shape looks like a water caltrop. The total population of the area is about five million and they are facing similar water quality and environmental degradation problems as Taihu.

Dianchi Lake⑥ (E102°38', N24°45')

Dianchi Lake is a freshwater lake located in the southwest of Kunming city, Yunnan Province, a few kilometers away

from the city center. In ancient times, the lake was called Diannanze, also called Kunming Lake. The historical book *Post Han Dynasty and Southwest Minorities* recorded: "This city has a lake that extends around 200–300 miles. The headstream is sufficient and water is like in backward flow." This description gave the name of the lake. It is a geologically fault formed lake at the height of 1,886 m above sea level. The lake used to be among the top five in size in China but has shrunk to below 300 km² in recent decades. Together with Taihu, Dianchi is considered as the most ecologically degraded water body characterized by algae blooming and general eutrophication.



Chinese Lakes, Figure 1 Location of major Chinese lakes; the numbers on the map refer to the respective numbers in the text.

Erhai Lake⑦ (E100°11', N25°47')

Erhai Lake was called Yeyuze or Kunmingchi Lake in ancient times. It is located in Dali Bai Autonomous Prefecture in west Yunnan Province. The length from north to south is about 40 km and the average width from east to west is 5–6 km. The average water depth is 12 m and the deepest place is about 23 m, in the east of the lake. The area of the lake is 246 km and the storage capacity is 2.95 billion cubic meters.

Jingbo Lake⑧ (E128°56', N43°52')

With the original name of Meituohu Lake, Huhanhai Lake, and Bi'erteng Lake, Jingbo Lake is located in Ning'an County, Heilongjiang Province, and in the upper reaches of Mudanjiang River. The length from north to south is 45 km and the widest distance between east and west is only 6 km. The lake area is about 95 km² with a storage capacity of 1.63 billion cubic meters. The south part of lake is shallow and the north is deep with a maximum depth down to 62 m. The formation of this lake is identified to be caused by ancient volcanic eruptions.

Wudalianchi Lake⑨ (E126°06', N48°18')

Wudalianchi Lake is located in the upper reaches of Baihe River, which is the tributary of Mohe River, 23 km from Dedou County. The lake is the northernmost lake for China.

It has been recorded in history books that, in the year 1719, two volcanos named Laohei Mountain and Huoshao Mountain in this area erupted, the magma jammed Baihe River and formed the present Wudalianchi Lake. Today, the lake area is a popular tourist attraction and it is also listed on the UNESCO's World Geological Park.

West Lake⑩ (E120°08', N30°15')

There are several lakes in China with this name. The best known one is the beautiful one located in the west of Hangzhou City. The total area is about 5.6 km with an average water depth of 1.5 m. The lake is divided into five parts, namely, Outer Lake, Beili Lake, Yue Lake, Xili Lake, and Xiaonan Lake. In ancient times, there was once a shallow bay here, evolving into a lake little by little. In the three directions of the lake stand hills. The Baidi Bank and Sudi Bank lie in the lake, forming two chains. There are three small islands in the central part of the lake. The lake is the best known lake in China by the public thanks to its scenery surroundings around the lake with many ancient inscriptions, structures, and stone sculptures. The lake area is also listed on the UNESCO's World Heritage Catalogue.

Qinghai Lake⑪ (E100°11', N32°58')

With the original name of Xihai, Qinghai Lake is located in northeast Qinghai Province. Hydrologically, it belongs

to the Chaidamu Inland Basin. This saline lake is considered as the largest lake in China (about 4,300 km²). In Mongolian, it is called “Kukunuoer” and in Tibetan with the name “Cuowenbu,” and they all means a “blue lake.” The lake is surrounded by mountains. In the north and east, there lie Datong Mountain, Tongbu Mountain, and Riyue Mountain of the Qilian Mountain range, the height of which is between 4,000 and 5,000 m; in the south and southwest, there stands Qinghainan Mountain, with the height over 4,000 m. The Qinghai Lake Basin is in the center, the lowest part of the lake area. The lake area is rich in fishery and migration birds, many of the species are on the national protection lists.

Zhaling Lake and Erling Lake^⑫ (E97°14', N34°54' and E97°43', N34°50')

Zhaling Lake (550 km²) and Erling Lake (600 km²) are located in Maduo County in Guoluo Tibetan Autonomous Prefecture and Qumalai County which belongs to Yushu Tibetan Autonomous Prefecture in Qinghai Province. Zhaling Lake is in the west and Erling Lake is in the east. Hydrologically these two sister lakes belong to the Yellow River Basin. The local Tibetan people, who have lived in the lake area with a long history, call Zhaling Lake “Cuojialang,” meaning the white long lake; and Erling Lake for “Cuolelang,” meaning the blue long lake.

Namucuo Lake^⑬ (E90°35', N30°40')

Namucuo Lake is located in west part of Tibet but is classified as in Northern Tibetan Basin. It is the grand lake (1,960 km²) with the greatest height in the world. In Mongolian, it is named “Tenggeliha,” meaning “the lake in the sky.” The shape of the lake is like an oblong. The length from east to west is 70 km and the width from north to south is 30 km. The lake has a storage capacity of 76.8 billion cubic meters. In the south of the lake stands the grand Nianqingtanggula Mountain and in the north and the northwest are small hills. There are three islands on the lake. In the southeast, a peninsula stretches into the lake. The peninsula is formed by limestone and the characters of karst topography are predominant.

Yangzhuoyongcuo Lake^⑭ (E90°43', N28°58')

Yangzhuoyongcuo Lake is also called Baidi Lake and in Tibetan it is named “Yumucuo,” meaning “the lake of swan.” The shape of the lake is like the claw of hen. The bank of the lake twists greatly. In the areas of Zhamalong and Baidi in the north part, there is the narrowest part of the lake with an extent of only 1–2 km. The rest three sides of the lake are wide and the extent is 3–8 km. The lake line is 250 km long. The height of the lake is 4,441 m (above mean sea level) with an area of 638 km². The depth of the water is 30–40 m, and the deepest place is 59 m. It is the largest inland lake in Southern Tibetan Basin with a storage capacity of 16 billion cubic meters. Besides, there are a number of small lakes around Yangzhuoyongcuo, such as Kongmucuo, Chencuo, and Bajiucuo. Some of

them connect directly with Yangzhuoyongcuo, and some only connect the lake during the wet period. In this way, the lakes form the Yangzhuoyongcuo lake chain.

Hulun and Beier Lakes^⑮ (E117°23', N48°57' and E117°44', N47°50')

Hulun Lake is also called Dapen Lake. Geographically it is located in the northeast Chinese border area, on the grassland among Xinbaerzuoqi, Xinbaeryouqi, and Manzhouli City in the Inner Mongolia Autonomous Region, but hydrologically classified to belong to Heilongjiang River Basin. It is 80 km long and 35 km wide, with a perimeter of 375 km. The lake area is about 2,300 km² and the storage capacity is up to 11 billion cubic meters. The deepest place is 8 m. It is one of the biggest lakes in the Inner Mongolia Autonomous Region. Together with the Beier Lake, which is much smaller (600 km²), located on the south of the grassland and the Sino-Mongolian frontier, the two lakes are also called sister lakes.

Daihai Lake^⑯ (E112°40', N40°37')

Daihai Lake is located in Liangcheng County in the Inner Mongolia Autonomous Region. It is a rift valley-shaped lake surrounded by mountains. The lake basin lies in the southeast of the basin. It is roughly 20 km long and 10 km wide. The area of the lake is about 133 km² and the storage capacity is 1.33 billion cubic meters. The deepest place is 18.4 m. The mineralization of the lake water is as high as 2.5 g/L and it is classified as inland saltwater lake since there is no outlet.

Luobupo Lake^⑰ (E90°38', N40°20')

Luobupo Lake (Lop Nur) is located in the east of Talimu (Tarim) Basin in Xinjiang, which is China's largest inland basin. In ancient times, it was called Zeyan Lake or Puchang Sea. In Mongolian, it is known as Luobuluoer, which means the lake converging many rivers. Unfortunately, this oasis in the Gobi desert gradually dried up and disappeared during 1950s due to desert expansion and human activities. According to historical books, this ear-like lake had area of over 5,000 km² and was a famous inland lake in Chinese history with the finding of some archeological facts such as the ancient kingdom of Loulan.

Chakayanchi Lake^⑱ (E99°06', N36°42')

Chakayanchi Lake is located in northeast corner of Qaidam Basin in Qinghai Province. In the north, it is near Kukuluorling Mountain of Qilian Mountain Range, and in the south it is close to Wangduoxiu Mountain. The lake shape is like an ellipse. It is 14.8 km long and 9 km wide, with an area of around 105 km². The area around the lake is one of the China's famous lake-salt producers.

Bositeng Lake^⑲ (E87°03', N41°58')

Located in the middle of the Xinjiang Uygur Autonomous Region, Bositeng Lake is also called Bakaci Lake. The

first description of this lake can be found in Chinese history books in Han Dynasty and Northern Wei. With a lake area of nearly 1,000 km², it is considered as the largest lake in Xinjiang and one of the largest inland freshwater lakes in China.

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CIRCULATION PROCESSES IN LAKES

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Introduction

The dynamic processes in a lake are governed by forces exerted on the water body and forces acting within the water mass. The direct circulation generating mechanisms are the wind, which transfers momentum and energy to the water surface, river through-flow, and atmospheric heat exchange and also heat exchange between water and sediment, which gives rise to density currents. In oceans and large enclosed seas different atmospheric pressure changes over the water surface force large water masses to move, which means that this is relevant also for the Caspian Sea. Tides are very minor even in the biggest lakes. The wind generates currents directly when momentum is transferred to the water surface. When the wind has ceased to blow there are slow back-forth water movements called seiches. All currents are modified by the bottom configuration and the density stratification. The currents are influenced by the rotation of the Earth. On the northern Hemisphere there is a tendency for an inflowing river to follow the right-hand side of the lake. The different circulation phenomena are described below.

Wind-induced circulation

When the wind is acting on a lake surface, momentum is transferred to the water. The water surface is set up slightly in the wind direction. The setup depends on the wind speed and water depth, as described below; the slope of the surface is very minor of the order 10⁻⁶, i.e., mm/km. There is a force balance between the wind shear (and partly also the bottom shear from the bottom current) and the gravitational forces against the wind due to the

tilting of the water surface. In a homothermal lake, which is neither extremely shallow nor deep, the velocity profile is as shown in Figure 1. The surface velocity is as a rule of thumb 2% of the wind velocity. In very shallow lakes of depth about 1 m, the currents along the shores are most often in the wind direction, while the return current is in the middle of the lake. Even in lakes as small as 10 km² and depth of 10 m, the circulation is influenced by the Earth's rotation. The surface current tends to turn to the right related to the wind direction.

The slope of the water surface can be determined by balancing the wind force, τ , and the gravitational force from the tilting. Neglecting the bottom shear, mainly because its direction is not obvious, the gradient, I , of the water surface is

$$I = \frac{\tau}{(\varphi g h)}$$

where φ is density of water, g is the acceleration of gravity, and h is the water depth. The shear force from the wind is related to the wind speed as

$$\tau = \varphi_a C_d W^2$$

with W as wind speed and C_d as a drag coefficient, which is about $1.0 \cdot 10^{-3}$ or slightly higher and to some extent depends on the stratification of the air. The atmospheric density is φ_a .

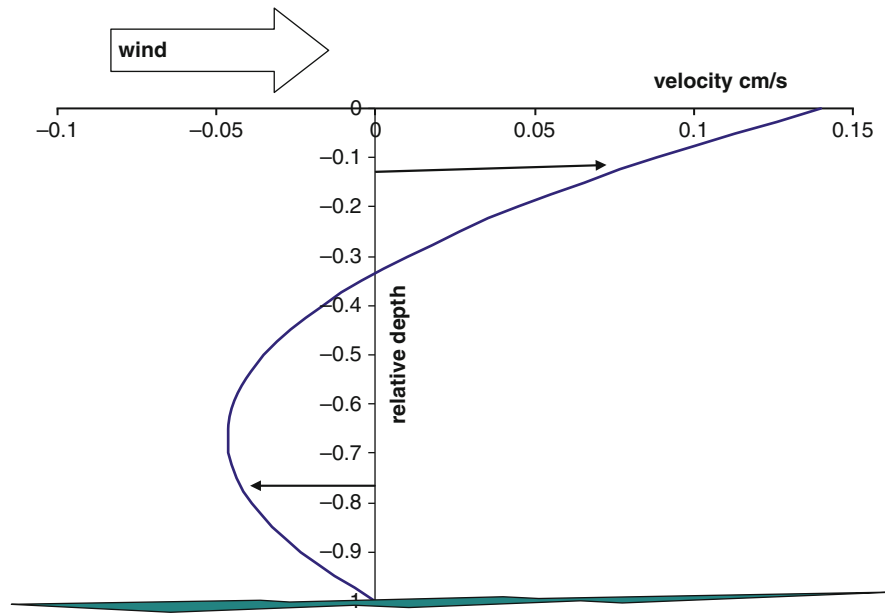
As an example consider the situation when a 7 m/s wind blows over a 3-km-long and 6-m-deep lake. The surface current will be about 14 cm/s, the wind shear about 0.06 N/m², and the slope of the water surface $1.0 \cdot 10^{-6}$, which means that the water level difference between the down- and upwind parts of the lake is only 3 mm.

Mathematical models of wind-induced circulation in complex lake basins have been in use since more than 35 years. The wind shear and its distribution over the lake surface are required as input and also the bottom topography of the lake and the stratification of the water (unless the model is run over a very long time and the temperature development is included in the model). Equations for determining the vertical mixing of momentum must be part of the model or a priori values of the vertical eddy viscosity and its distribution must be used. Correct estimation of the vertical eddy viscosity is crucial for good modeling results.

Seiche currents

Already in the 15th century periodic oscillations of the water surface were observed on Lac Lemman (Lake Geneva). The periodic movement was named seiche. The character of the seiche is determined by the geometry of the lake and by the water stratification. The oscillations may be free, as when the wind ceases to blow, or forced by rhythmic changes of the wind or by other external forces.

A surface seiche has a short period (minutes or hours) and small amplitude (mm or cm). The theoretical



Circulation Processes in Lakes, Figure 1 Wind-induced velocity profile in an elongated homothermal lake of depth of about 4–8 m when the wind speed is about 7 m/s.

period, T , in an elongated lake of length L and mean depth h with homothermal water is

$$T = 2 \frac{L}{\sqrt{gh}}$$

Since the amplitude is minor, the currents when water masses are moving back-forth are also minor. However, in very shallow lakes the seiche currents can be significant. The mean current, u , in the middle of a lake is

$$u = 2A \frac{\sqrt{g/h}}{\pi}$$

with A as the amplitude of the seiche, i.e., half the maximum difference of the water level at the two end shores. In the Hungarian Lake Balaton, which is 80 km long and has a mean depth of less than 3 m, a 7 m/s wind should cause the water surface to tilt $2 \cdot 10^{-6}$, which is an amplitude of 0.08 m. The mean seiche current is then about 10 cm/s. Wind speeds of 20–25 m/s ought to give rise to back-forth currents greater than 1 m/s, which also has been observed.

During summer it is very common that a lake is stratified with warm rather homothermal water, epilimnion, above colder denser water, hypolimnion. The temperature drop is within the metalimnion over a few meters. When the metalimnion is rather thin this layer or border between the epilimnion and hypolimnion is called the thermocline. When there is a setup of the water surface, also the thermocline must tilt, but in different direction than that of the surface and with a much stronger slope. If the thermocline is very sharp and the stream velocities are low, the slope of the thermocline should be related to that of the water surface as

$$I_{\text{thermo}} = -I_{\text{surface}} \frac{\varphi}{\Delta\varphi}$$

$\Delta\varphi$ being the density difference between the hypolimnion water and the epilimnion water.

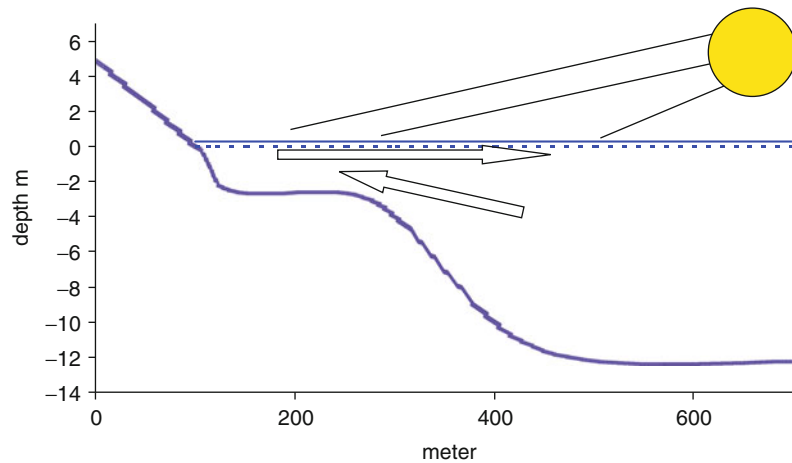
Also the thermocline may oscillate, but with a large amplitude and with a long period (hour, days). Since the amplitude of the internal seiche is large, large water masses are set in motion. If the thermocline is close to the bottom, the generated currents can be quite large. It may be that the thermocline is forced to tilt so much that it reaches the water surface near one end of the lake. This means that bottom water reaches the surface. This phenomenon is called upwelling.

Through-flow

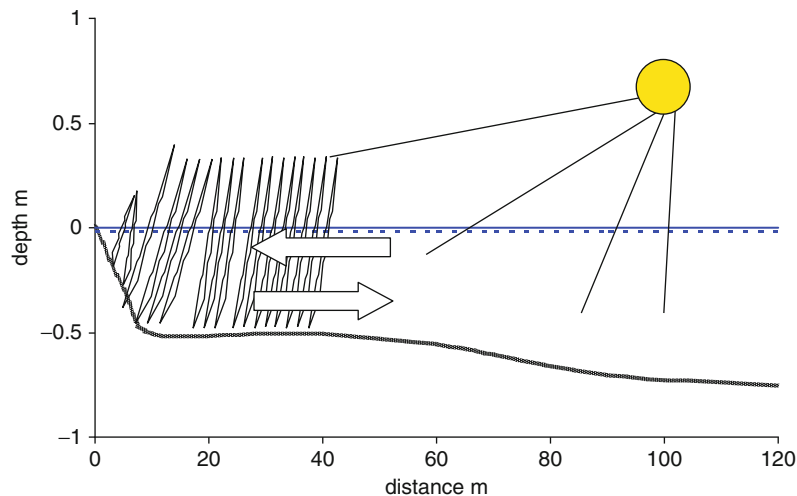
A river entering a lake generates water movements, but since the lake is deeper and wider than a river, the currents are generally minor and observed only near the river inlet. Because of the Earth's rotation there is a small tendency that the river initially follows the right-hand side of the lake. More important is the effect of the different density of the river water and the lake water. After initial mixing the river water may be layered within certain depths.

Density currents

Horizontal density differences or anomalies within the lake water always generate currents. Nature strives to obtain density-stable conditions. Horizontal density gradients tend to be established when the water is heated differently (differential heating) over the lake. It may be that more solar radiation is received per unit volume in shallow parts such as bays as compared to deep parts of a lake,



Circulation Processes in Lakes, Figure 2 Differential heating causing convective circulation and water exchange between warmer bay water and the colder lake proper.



Circulation Processes in Lakes, Figure 3 Differential heating due to shading by vegetation resulting in warmer water in the lake proper and movement of surface water into the vegetated area and corresponding outflow of water near the bottom.

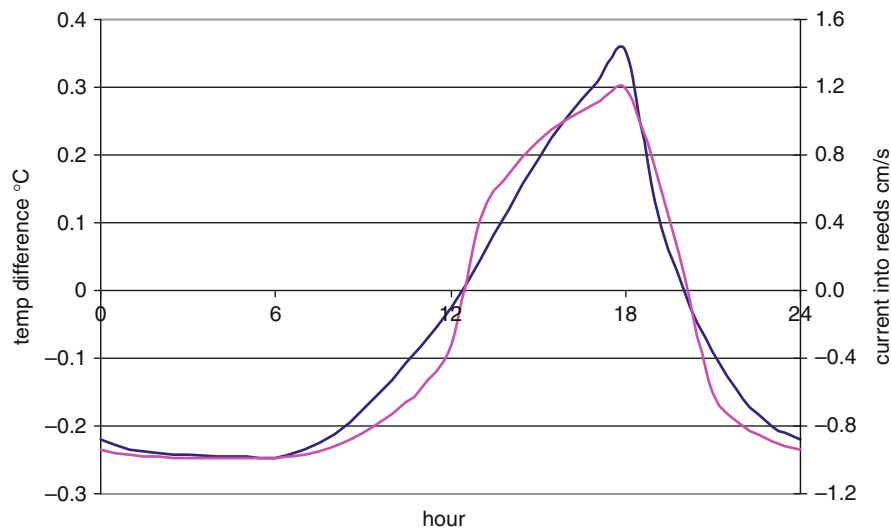
Figure 2, or it may be that some parts of the lake are shaded and less exposed to solar radiation than other parts, Figure 3. Horizontal temperature gradients may also be caused by patches of high turbidity, which absorb more of the heat closer to the surface than clear water does. In the winter, heat released from the sediments generates slow density currents; see the article “*Ice Covered Lakes*”.

Currents induced by differential heating may reach up to 10 cm/s, but are more commonly only a few cm/s or even less. When the differential heating is due to shading, these convective currents tend to be in a different direction during daytime and nighttime. When the heat flux is from the sediments the velocities are very small and not measurable, but are continuous for most of the ice covered period.

As a quantifying example of differential heating, in a study of Lake Velen in Sweden it was found that in early June the water temperature in a shallow bay, 2.5 m deep, tended in the course of the day to become 1°C warmer by late afternoon than the surface water in the lake proper and then during the night return to the same temperature as the water outside the bay. The current, c , induced by the temperature gradient is sometimes crudely estimated from the sluice-gate (lock) equation:

$$c = 0.5 \sqrt{g^I h}$$

where g^I is the densimetric gravity $\Delta\phi/\phi g$. In the above given example the convective surface current out of the bay into the main part of the lake would be 3 cm/s.



Circulation Processes in Lakes, Figure 4 Temperature difference between open water and reed-covered area in Lake Kranke, Sweden, and surface velocity generated by the differential heating. The surface currents are into the reeds during daytime and out of the reeds during nighttime.

When parts of the lake surface is shaded, it tends during sunny days not to be heated as much as where there is open water. During daytime a circulation pattern as the one shown in [Figure 3](#) develops. During nighttime the open water cools faster and the circulation is reversed. An example from Lake Kranke in southern Sweden is shown in [Figure 4](#). The temperature difference reaches 0.3°C and the surface current about 1 cm/s.

Circulation in ice covered lake induced by heat flux from the sediments is discussed in the article on ice covered lakes. These currents are of the order m/day.

Cross-references

[Hydrodynamics and Circulation of Fjords](#)
[Hydrodynamics of Very Shallow Lakes](#)
[Ice Covered Lakes](#)
[Internal Seiches](#)
[Mixing in Lakes](#)
[Stratification and Mixing in Tropical African Lakes](#)
[Stratification in Lakes](#)
[Surface Seiches](#)
[Thermal Bar](#)
[Thermal Regime of Lakes](#)
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[Water Exchange Between Littoral Zone and Open Lake Water](#)

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CLASSIFICATION OF LAKES FROM HYDROLOGICAL FUNCTION

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Definition

Lakes can be classified in different ways, according to their *geological* origin (see [Classification of Lakes from Origin Processes](#)), according to their *trophic* state (see [Trophic Lake Classification](#)), which is according to the biological status, according to the *thermal regime* (see [Thermal Regime of Lakes](#) and [Stratification in Lakes](#)), which is related to the climate, or according to the hydrological conditions relating to the character of the in- and outflows. In this entry, lakes are classified according to their *hydrological function* (see also [Water Balance of Lakes](#)).

Classification of Lakes from Hydrological Function,
Table 1 Hydrological classification of lakes

Inflow	Outflow	Lake type	Settings
Surface	None	Terminal	Large lakes
Surface	Surface	Spillover	Most common lakes
Groundwater	Surface	Spillover	Downstream sand formation
Groundwater	Groundwater	Closed pond	Groundwater system

The hydrology of a lake is determined by the water inflows and outflows including precipitation on and evaporation from the lake surface and, thus, by the climate and the geological settings. Some lakes have no outflow. These lakes are *terminal lakes* or *closed lakes* often referred to as *endorheic lakes*. Evaporation from the lake is considerably larger than the precipitation on the lake. The lake area is large relative the full river basin area. The lake level varies much and thus also the lake surface area. The water is usually salt. The lakes are often very big such as the Caspian Sea, Lake Chad and very sensitive to climate variations and human impact, the Dead Sea and the Aral Sea. If the climate becomes more humid such a lake may turn into a spillover lake, or such a lake may have been a lake with spillover in a previous climate.

Most lakes have outflows. The lake level does not vary very much, since increased water level means increased outflow. These *spillover lakes* or *overflowing lakes* may have one or several *surface inflows* and also groundwater inflows. Groundwater inflows are usually minor if there are inflowing streams. Groundwater inflows dominate if the lake is the outlet of a *spring* or if the lake is situated within or downstream a *sand formation*.

Some lakes or ponds are merely a part of the *groundwater system*, with the inflow as well as the outflow being groundwater flow. Glaciated hollows filled with groundwater may be such lakes, but such kettle lakes may also have some surficial inflows or outflows.

The classification is shown in Table 1.

The classification can be driven further by considering the inflow variations of the annual cycle of precipitation, evaporation from the lake and the inflow.

CLASSIFICATION OF LAKES FROM ORIGIN PROCESSES

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Introduction

There are 100 million lakes in the world larger than 0.01 km². Lakes can be classified in different ways, according to their *geological* origin, to their *trophic* state (see *Trophic Lake Classification* in the Encyclopedia),

which is according to the biological status, according to the *thermal regime* (see *Thermal Regime of Lakes* and *Stratification in Lakes*), which is related to the climate, or according to the *hydrological conditions* relating to the character of the in- and outflows (see *Water Balance of Lakes* and *Hydrological Classification of Lakes*). In this entry, lakes are classified according to their geological origin. A lake is formed when water fills a depression. A depression can have been formed in different ways. Lakes are mainly created as consequences of *tectonic*, *glacial*, or *fluvial processes* but there might also be other processes involved. Tectonic lakes are deep. Glacial lakes are found where there has been land ice. The glacial lakes are rather shallow and this type of lakes is often found clustered within a region. The fluvial lakes are less common. They are very shallow.

Glacial lakes

There are a large number of glacial lakes in Northern America, Scandinavia, and Russia. These lakes were created due to the glaciation during the Pleistocene. Depressions were formed by glacial features as moraines and glacial scour. The climate is such that precipitation dominates evaporation and thus favors the existence of lakes. The glacial lakes constitute almost 50% (1,250,000 km²) of the surface area of all lakes. The lakes are formed either in direct contact with the ice, behind depositions from glaciation, or depressions eroded during prior glaciation. The Great Lakes of North America are glacial lakes but most of the glacial lakes are quite small and instead abundant in certain regions such as in the Finnish Lake District. Some glacially formed lakes may be deep. Lakes that are formed in long glacially formed valleys are fjord lakes. If they are directly attached to the sea, as there are so many examples of in Norway, they are ordinary fjords. Examples of deep glacial lakes can be found in the Scandinavian mountains. The deep lakes in Switzerland and northern Italy may also be classified as fjord lakes.

Tectonic lakes

Tectonic lakes are created from the movement of the Earth's crust. The deepest and oldest lakes in the world have evolved from tectonic processes. The Caspian Sea is the biggest one with an area of about 370,000 km² (varying rather much since the Caspian Sea is a terminal lake), which is 15% of the world's lake area. The Caspian lake volume is 45% of that in all lakes. The other tectonic lakes when not including the Caspian Sea make up about 20% (525,000 km²) of the surface area of all lakes but since they are very deep 32% of the total volume of all lakes (76% including the Caspian Sea). The Caspian Sea and also the Black Sea were formed during the convergence of Africa and Arabia with Eurasia, when also the Mediterranean sea was formed. In Late Tertiary the Black sea was a terminal lake as the Caspian Sea is today. The extremely deep lakes, Lake Baikal and Lake Tanganyika, were formed during the early phases of continental rifting. There are also shallow tectonic lakes. Lake Chad is such

an example and Lake Okeechobee. Lake Chad is in a dry environment. It is formed in a low interior region of Africa due to subsidence. Lake Okeechobee was formed from the uplift of the ocean floor.

Fluvial lakes

Fluvial lakes are very shallow. Although they constitute almost 10% of all lake surface area, they hold only about 0.3% of the volume. Sediments transported by rivers may accumulate, for example, in river bends, and create a form of dam, or running water may excavate depressions. Meandering rivers may take a new course through a river bend and then a lake, oxbow lake, may be created. A river system with an oxbow lake often includes many such small lakes. Fluvial lakes may also be created near the coast, when longshore coastal currents deposit sediments that block river outflows. The fluvial lakes can be created due to processes acting over a longtime, or as a consequence of very extreme events.

Lakes formed by other processes

Some lakes have origin different from the three major ones. Lakes may be formed by volcanic activity, by solution in karst terrains, meteorites, and landslides or formed by the wind.

Volcanic lakes formed from volcanic activity can be found in Iceland, Italy, and New Zealand. In karst terrain there is solution of subsurface rocks by groundwater leading to formation of hollows which can be filled with water forming usually small *karst lakes*. This kind of lakes is common on the Balkan Peninsula.

Landslides may dam water in mountainous terrain. Lakes created in this catastrophic way may be temporary and can be drained again almost in a catastrophic way. Damming of rivers may also be due to *accumulation of plant material*. Mammals, especially the beaver may build dams so that a lake is formed upstream.

Lakes (*wind formed lakes*) can be formed by wind action. Sediments transported or eroded by the wind may form irregularities in the terrain. Windblown sand may block rivers. These lakes are shallow.

In large regions of the Northern Hemisphere the land is still rising. The sill between some shallow bays or fjords and the sea is slowly coming above the sea level cutting of the bays from the sea, and the bays and fjords turn into fresh water lakes sometimes called cutoff lakes. There are numerous such examples along the Baltic in the north of Sweden and Finland.

Of course, the very large dams are built by man. *Man-made lakes* or *reservoirs* are a very special form of lakes. They are found almost all over the world. They are described in several entries in the encyclopedia.

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Cross-references

[Lakes on Earth, Different Types](#)

[Origin of Lakes and Their Physical Characteristics](#)

[Paleolimnology](#)

CLIMATE CHANGE EFFECTS ON LAKES

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Introduction

The global environmental changes that are apparent today are mainly anthropogenic due to the growing human population and its high activity of resource consumption. The most obvious trends concerning ecosystem impacts are the anthropogenic changes in biological diversity and alterations in the structure and functioning of the food web. Climate change is one of the most important factors within the global change issues, and therefore, the impact of climate on ecosystems has been widely tested using historical data, experiments, and model simulations.

In temperate aquatic ecosystems, most of the ecologically important characteristics are influenced by climate change such as changes in temperature, evapotranspiration, frequency and magnitude of precipitation, wind, storm, and fire events, length of the ice-free season, and the depth of the mixed layer. In general, many water quality problems may worsen by climatic change, particularly those relating to eutrophication, such as bottom-oxygen depletion. However, an extreme uncertainty exists at any case-specific level, which is related often to specific characteristics of lakes (e.g., depth, retention time) and/or catchments, such as land use patterns.

In the following, four physical responses will be discussed followed by presenting an overview of ecosystem-wide changes and the potential effects of no direct-related drivers.

Ice cover

The timing of ice freeze and breakup, one of the longest and widespread limnological variables, has been used often as an indicator for regional climate change. Duration

of ice cover is driven by several meteorological variables, of which air temperature has been shown to be the most important one.

A long-term trend toward shorter periods of ice cover due to a later freezing and an earlier ice breakup has been reported for lakes around the northern hemisphere. The trend of an earlier ice-out increases the ice-free period and raises lake temperatures in spring in many reported studies from global distributed lakes. In Northern Europe, the duration of the ice cover period and the timing of freeze and breakup greatly affect lake systems, in particular, the succession events in plankton and partly underwater plant dynamics.

Water temperature

Surface water temperatures often show a strong coherent increase following the warming of air temperature across European lakes. A faster temperature rise in the spring (due to earlier ice-out dates) preceded the beginning of spring stratification, which may influence nutrient cycling and phytoplankton dynamics. Consequently, effects of higher water temperatures on the lake mixing regime could lead to dimictic lakes (fully mixed twice a year) turning into warm monomictic lakes.

Overall, temperature affects all physiological processes, thereby influencing the growth of organisms. The magnitude in which physiological rates change with respect to temperature is generally in good agreement with an Arrhenius formulation. For example, zooplankton found in lakes can tolerate fairly high summer temperatures, but small increases in the winter temperature, in some lakes significantly related to the timing of ice breakup, can strongly affect the overwintering and seasonal dynamics of zooplankton species such as *Daphnia* and *Eudiaptomus* through a strong temperature-dependent growth rate.

The survival and growth of fish species, for example, depends often on temperature. Thermal limits of some fish species, altered by global warming, can induce changes in spatial distribution. Temperature-induced changes in the growth rate of predatory fish may result in cascading effects through the entire food web.

Stratification

Most temperate deep lakes are stratified during summer, with a warm surface water (epilimnion) and cold deep water (hypolimnion). The most crucial triggering factors for the timing of phytoplankton blooms are light and turbulence, which are both influenced by stratification and therefore directly affected by climatic variation and change. Consequently, strong relationships between the timing and the winter climate were found in European lakes. Differences in the individual lake response depend often on the morphometry of the lake. For example, in Lake Constance (Germany) – a large and deep lake which generally is not covered by ice in winter – the spring bloom only occurs under stratified conditions, because reduced mixing increases light availability for phytoplankton. Generally, an enlarged mixing depth increases

the proportion of incoming light, which is attenuated abiotically within the mixed layer. This leads to a decrease in phytoplankton production averaged over the mixed layer with increasing mixing depth. By contrast, in shallow lakes with a lower mixing depth, the phytoplankton spring bloom is often associated with ice cover disappearance (determined by winter climate), influencing the light availability as observed for example in Lake Müggelsee, Germany, and Lake Erken, Sweden. Later in the year, conditions in the lake appear to be more complex and stratification becomes the predominant triggering factor. For example, longer periods of stratification can promote a dominance of potentially toxic cyanobacteria as higher water temperatures prolong the stratification period and create favorable conditions for cyanobacteria. Additionally, large cyanobacteria colonies (besides other phytoplankton groups) are resistant to grazing by zooplankton, especially in eutrophic lakes. These two mechanisms partly promote the dominance of cyanobacteria in stratified lakes at a warmer temperature regime. Longer periods of summer stratification and higher hypolimnetic temperature are also projected to cause increased hypolimnetic anoxia, or at least lower oxygen concentrations. This condition often leads to an enhanced phosphorus release from the sediment, in particular, important as phosphorus is the main limiting factor in lakes.

Hydrology

The inflowing water from streams and rivers and their loading depends very strongly on precipitation and land use, e.g., the intensity of agriculture. The amount of the inflowing water further affects the hydrological water residence time in the lake which further influences how long for example phosphorus molecules are recycled within a lake. Stratified lakes with a water residence time longer than 1 year have a higher potential to suffer from an amplified climate-related eutrophication as the warmer climate may intensify the stratification and thereby cause a P released from P-rich sediments. In contrast, in lakes with short residence time (months), the phosphorus released from the sediment is flushed out relatively quickly and therefore cannot contribute to next-year phytoplankton development. Decreases in water residence time, for example, through an increase in precipitation with an associated higher runoff, can decrease concentrations of nutrients, as water residence time scales the rate of the ecosystem response to chemical inputs and to climate change and variability. The water level of closed lakes where the hydraulic load is counterbalanced by evaporation and rather stable seepage serves as one of the best indicators of long-term climatic variation.

Ecosystem changes

Climatic changes relevant at a species level are likely to vary at the ecosystem scale among lakes. Weak links in food web interactions, in particular, dampen oscillations between consumers and resources. This implies that not all responses at a specific trophic level are propagated

to lower trophic levels or have significant impacts on ecosystem processes. Additionally, a prolongation of the climate signal due to food web interactions is possible as the signal of, for example, winter climate can be detected in the clear water phase in early summer (induced by high zooplankton grazing) or in summer phytoplankton composition and biomass. A system approach is necessary to examine the cascading effects in response to climatic change and variability. The magnitude of a climate-driven response of an autotrophic organism does not necessarily have to be mediated or cascaded to the heterotroph species, or vice versa. Another example indicates that a consecutive period of five mild winters led to a complete change of the spring phytoplankton bloom, from a dominance of diatoms and cryptophytes to a dominance of cyanobacteria in a German lake. This illustrates, furthermore, that the response of phytoplankton, and probably also other lake biota, to climatic variation might be totally different from the response of a warming trend, as many ecosystem processes are nonlinear. Furthermore, the nonlinearity in the response to environmental variables of animals and plant may cause progressive changes to be interrupted by drastic switches to a contrasting ecosystem state. One such example is the shift between the clear water (macrophyte dominated) and the turbid (plankton dominated) state of shallow lakes. A recent study in a Swedish lake showed that climate variability alone cannot explain such a shift, but is likely to amplify this to a multi-causal stress and, therefore, reduces the resilience of the clear-water state in shallow lakes.

Impacts of other anthropogenic drivers

In the past 40–50 years, many lakes, particularly in Europe and the USA, have been subjected to an anthropogenically caused increase in the supply of nutrients and other substances, e.g., organic pollutants. This supply decreased partly in the late 1980s or early 1990s. While improvements in wastewater treatment over the last decades have reduced inputs of nutrients from point sources, the increase in nutrients from diffuse sources is still a major problem and, for many lakes, remains the predominant concern. Additionally, catchment alteration, acidification, dam regulation, agriculture, and the waterborne sanitation solution can complicate a separation of the various influences on ecosystems. Therefore, to clearly disentangle the effects of climate on important lake processes from anthropogenic nutrient effects are very difficult. The effects of multi-stressors on ecosystems is very complex in particular, as the stochastic interplay of these effects and the nonlinear or time-lagged response of the food web are very difficult to foresee.

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Cross-references

[Climate Change: Factors Causing Variation or Change in the Climate](#)

[Hydrodynamics of Very Shallow Lakes](#)

[Ice Covered Lakes](#)

[Lake Ice](#)

[Thermal Regime of Lakes](#)

CLIMATE CHANGE: FACTORS CAUSING VARIATION OR CHANGE IN THE CLIMATE

Cintia Bertacchi Uvo

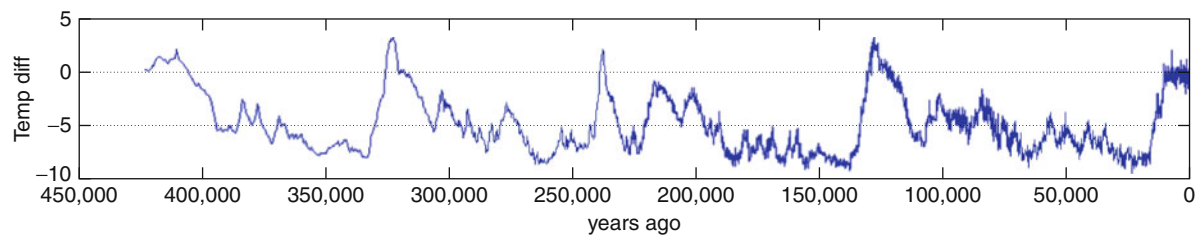
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Introduction

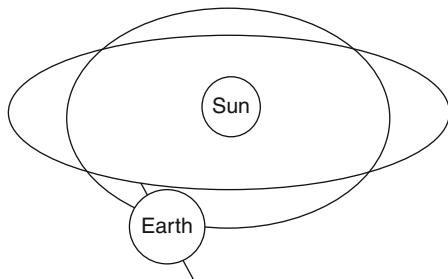
Climate changes are variations that happen in the climate on a certain location or globally and on different time perspectives. On a geological time perspective, the climate of the Earth has changed drastically in the past. It has experienced long periods (thousands of years) of very high or very low temperature if compared to the temperature experienced today ([Figure 1](#)). After the latest ice age (about 13,000 years ago), the variations in climate have been milder if compared to the previous ones. Changes in the past climate in a geological perspective, also known as paleoclimate, can be inferred through traces left on glaciers or on ice sheets, tree rings, lake beds, caves, among others.

Causes and consequences

The causes for changes in climate can be many, and the consequences of each of them can last for longer or shorter time periods. On a *geological* perspective, the drift of the continents have caused changes on the global climate that follows a geological time scale, that is, hundreds of thousands of years. On the other hand, *volcano* outbreaks that are also related to the continents' drift can change the climate on a shorter time scale by throwing ashes into the atmosphere. The ashes shade the solar radiation by increasing the albedo of the upper atmosphere and cool down the atmosphere below. Climate changes caused by volcano outbreaks can last from a few days to a few years depending on the intensity of the outbreak, the amount of ashes liberated, and the altitude reached by the ashes. An example of the consequences of volcano outbreak is the year 1816, known as the “year without a summer.” From late spring to early fall that year, temperatures were abnormally low mostly in the Northern



Climate Change: Factors Causing Variation or Change in the Climate, Figure 1 Temperature difference between today's global average temperature and past global temperature for the latest 450,000 years as estimated by the Vostok ice core, Antarctica (Petit et al., 1999).



Climate Change: Factors Causing Variation or Change in the Climate, Figure 2 Example of variation of Earth's orbit around the Sun.

Hemisphere due to the ashes thrown into the atmosphere by the eruption of the Mount Tambora volcano on the island of Sumbawa, Indonesia, on April 10 and 11, 1815 (Stothers, 1984).

Solar radiation

The *solar radiation* is an important factor determining the climate. The amount of radiation that reaches the Earth and how it is distributed over it are key factors for the definition of the climate in such way that changes in solar radiation amount and distribution cause changes in the climate. Changes in solar radiation amount and distribution can be caused by changes on the inclination of the Earth's axis in relation to the Sun, which affects the distribution of the sun radiation, or by changes on the Earth's orbit around the Sun that affects the intensity of the solar radiation received by the Earth. Such changes cause climate changes on a very long time perspective (hundreds of thousands of years). An example of such variation on the Earth's orbit can be seen on Figure 2.

In addition to that, the solar activity also varies and with it the intensity of the solar energy that reaches the Earth. A cycle of about 11 years in the sun activity is well known, and that impacts the Earth climate, creating a cyclic change on the climate. The cyclic solar activity can be seen in the number of sunspots observed per year as represented in Figure 3.

Cyclic climate changes on a relative short time perspective are called climate variability. Several other natural

phenomena can impact the climate causing changes or variability in climate. Many of these phenomena are related to the circulation of the oceans or of the atmosphere, or of both ocean and atmosphere. The Gulf Stream and the El Niño–Southern Oscillation (ENSO) are among the best known of such phenomena.

ENSO

ENSO is a climate phenomena caused by the interaction between the Pacific Ocean and the atmosphere. It presents an oscillation of 2–4 years and impacts the climate all around the world. The ENSO oscillation can be seen at the temperature of the surface of the Central Pacific Ocean. Figure 4 shows the difference between the sea surface temperature and the average sea surface temperature on Central Pacific. Periods when the sea surface temperature is above normal (red color) are named El Niño events and below normal (blue color) are named La Niña.

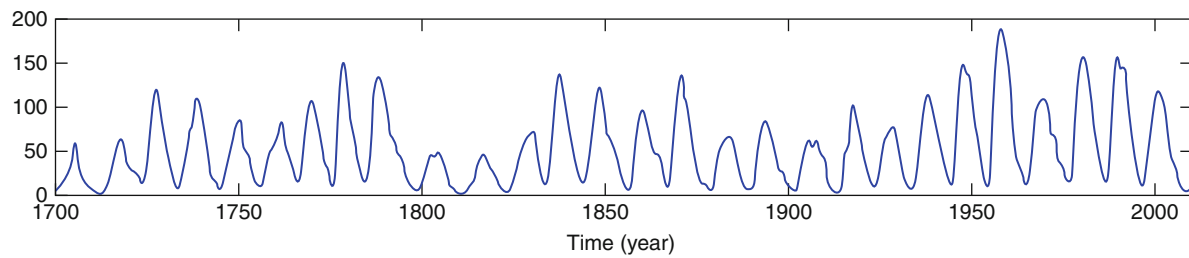
ENSO events change the climate of the Earth regionally and seasonally so that some regions become warmer than normal or colder than normal, or drier or wetter as exemplified in Figure 5 for the winter in the Northern Hemisphere (December–February).

Human activities

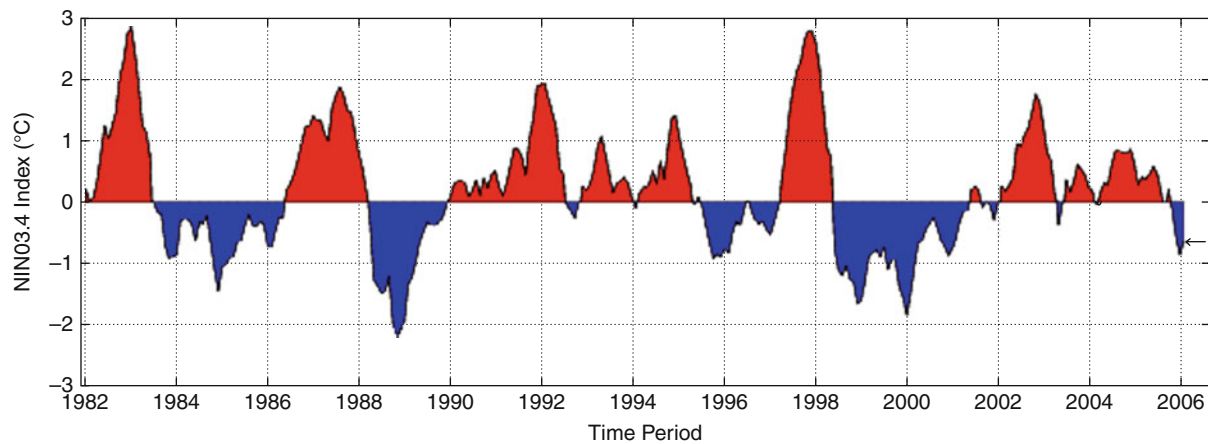
Human activities can also cause climate change that can be on a small area or globally. For instance, the night temperature on a city is normally higher than the temperature on rural areas around it. This is known as heat island effect caused by the concentration of buildings, cars, asphalt, etc., typical of urban areas.

Greenhouse gases

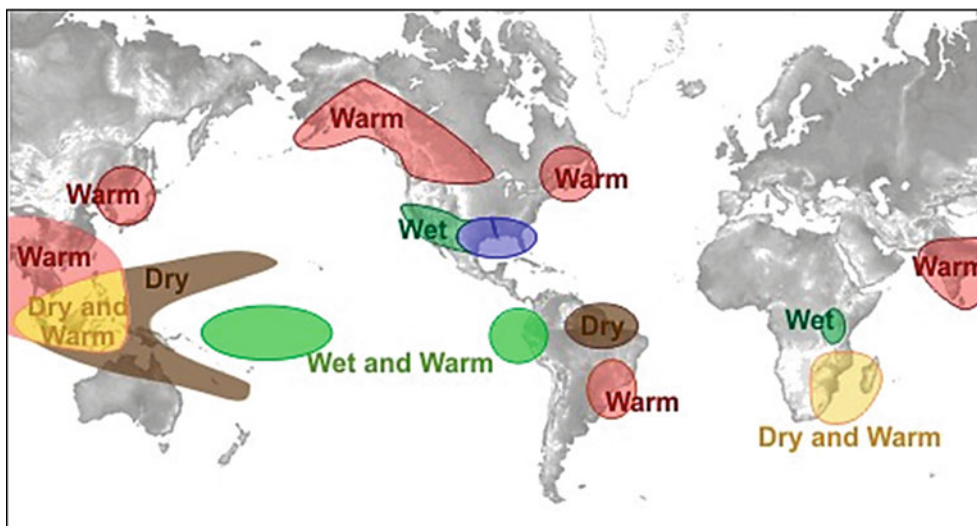
After the industrial revolution, the increase of *greenhouse* gases emission has also impacted the climate of the Earth. A small but constant increase of the atmosphere's average temperature has been observed since then as seen in Figure 6. Today's technology for studying climate change makes use of global climate models that are, in simple words, computer programs for solving mathematical equations that describe the circulation of the atmosphere and the oceans. Using such technology, it is possible to infer the climate in the future. Such models estimate an increasing warming climate for the next 100 years if the



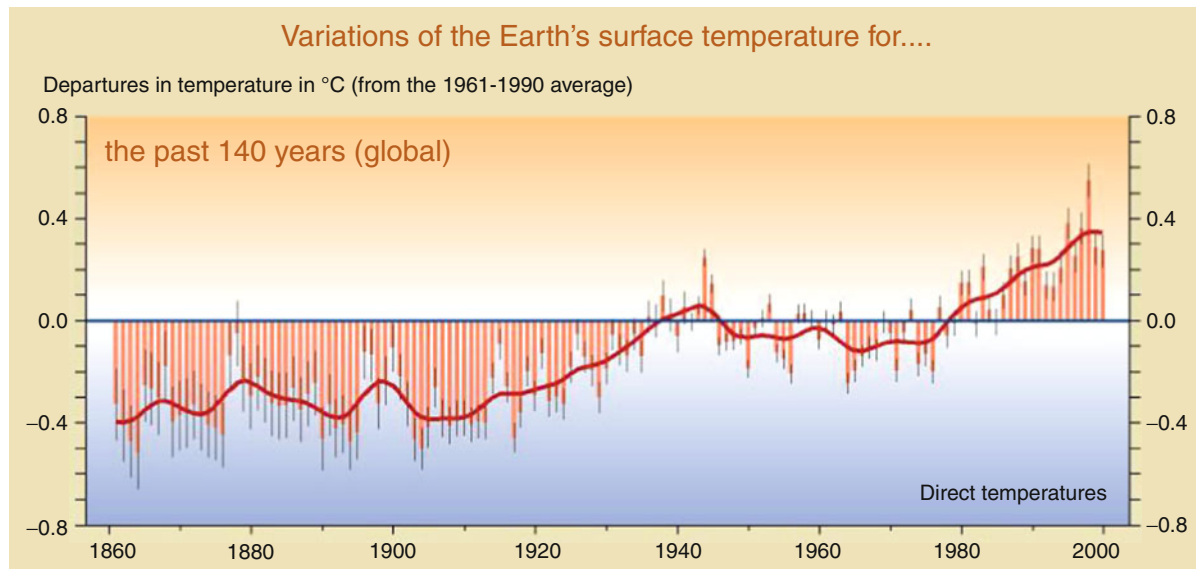
Climate Change: Factors Causing Variation or Change in the Climate, Figure 3 Yearly sunspot number since 1700 (Data provided by SIDC-Solar Influences Data Analysis Center).



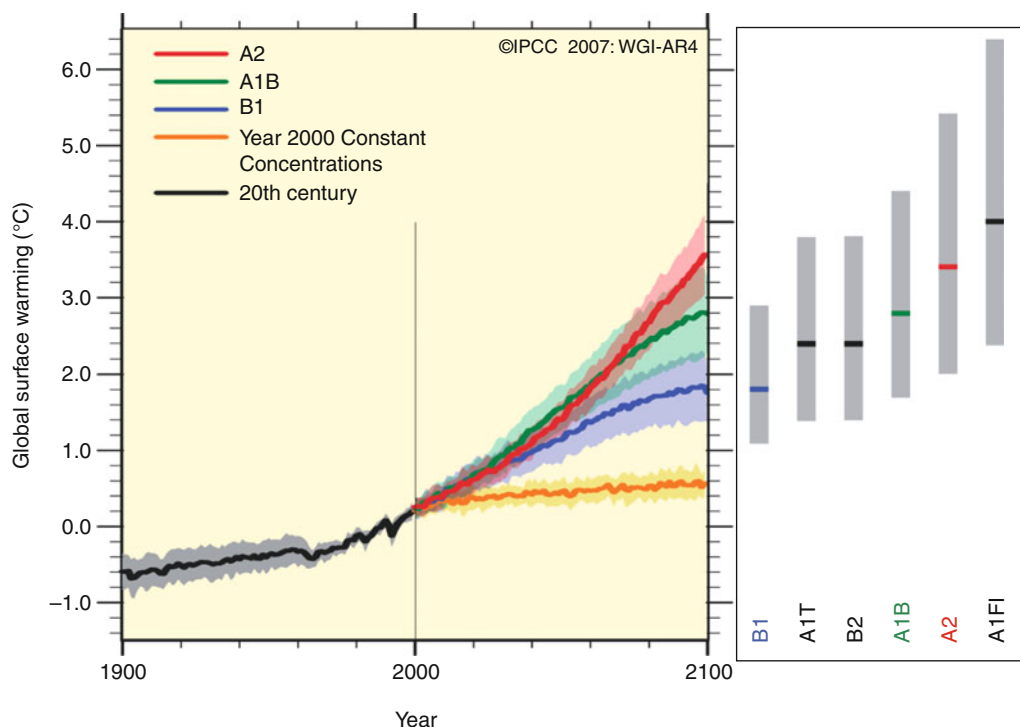
Climate Change: Factors Causing Variation or Change in the Climate, Figure 4 NINO3.4 index (degrees Celsius), representative of the ENSO phenomenon.



Climate Change: Factors Causing Variation or Change in the Climate, Figure 5 Effects of El Niño events during the December-February season (Source: http://www.srh.noaa.gov/jetstream/tropics/enso_impacts.htm).



Climate Change: Factors Causing Variation or Change in the Climate, Figure 6 Difference between the average Earth surface temperature from 1961 to 1990 and the annual average since 1860 (Source: IPCC, 2001).



Climate Change: Factors Causing Variation or Change in the Climate, Figure 7 Future scenarios of global surface warming relative to six CO₂ emission scenarios (IPCC, 2007) A1: world of very rapid economic growth, population peaks in mid-century, and rapid introduction of new and more efficient technologies. A1F1: A1 with fossil intensive energy resources. A1T: A1 with nonfossil energy resources. A1B balance across all sources. B1: convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2: world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. A2: very heterogeneous world with high population growth, slow economic development, and slow technological change. The gray bars to the right indicate the best estimate (solid line within each bar) and the likely range for the six scenarios at 2090–2099 relative to 1980–1999 (Source: IPCC, 2007).

emissions of greenhouse gases continue as they are today (scenario A2 in [Figure 7](#)). A smaller warming is expected if emissions are reduced (scenario B1 in [Figure 7](#)).

All these mentioned causes for climate change are continuously acting and interacting with each other. The result of such a complex system is that in some periods, they can add on their impacts enhancing them or counteract each other's effects and fading their impacts on the Earth's climate.

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Cross-references

[Climate Change Effects on Lakes](#)

COASTAL LAGOONS

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Synonyms

Inland coastal water bodies

Definition

Coastal lagoons. Water bodies connected to the sea through one or more channels, known as inlets, which often cuts through a narrow barrier island of erodible material. Water exchange occurs between the lagoon and the sea because of tides, river flow, wind, and waves. Depending on the ratio between the salt water and the freshwater flows taking part in this exchange, stratified conditions may develop and density-driven currents will be important for the mixing and environmental conditions of the lagoon (compare *estuarine hydrology*). Coastal lagoons may close, intermittently or permanently, if the water exchange is not sufficient to keep the inlets free of sediment.

Introduction

Lagoons are common water bodies in many parts of the world and it has been estimated that approximately 13% of the world's coastline is occupied by lagoons (Barnes, 1980). The occurrence of lagoons is rather similar on the different continents, but they tend to be less numerous in Europe (5% of the coastline) and more common in Africa (18%) and North America (18%). The main factor behind the formation of coastal lagoons was the rising sea level during the Holocene in combination with coastal processes acting on marine deposits (Kjerfve, 1986). Coastal lagoons are typically oriented along the coastline and are shallow water bodies with depths often not exceeding a few meters. Lagoons are often strongly influenced by human activities that include multipurpose, often conflicting usages, such as navigation and anchorage, aquaculture, recipient for wastewater and agricultural drainage, and recreation. Since these water bodies in general are sensitive to external water and pollution inputs, the management of lagoons is a complex issue, involving physical, environmental, social, and economical aspects.

Lagoons typically act as deposition basins for sediment and organic matter, which originate either from the sea, adjacent land areas, or discharging rivers (see [Sedimentation Processes in Lakes](#)). Thus, in a geological time frame, the lagoons have a short lifespan, experiencing infilling and closure (Woodroffe, 2002). The availability of sediment and organic matter implies high primary and secondary production rates, which is one reason for the frequent use of lagoons for aquaculture and fishery (Miller et al., 1990). Density variations and *stratification*, primarily due to salinity, although temperature effects may be significant as well, often prevail in a lagoon. However, the conditions in the lagoon may vary from freshwater to hypersaline, depending on the relative importance of the freshwater input from rivers and the water exchange with the sea due to the tide (evaporation could also be a factor in some cases).

There are large variations in the size and general properties of lagoons. Kjerfve (1986) performed a comparative study on coastal lagoons and presented basic data from a number of case studies worldwide. The surface area of the lagoons investigated ranged from 1 to almost 13,000 km², with mean depths being below 5 m in most cases. The lagoons studied experience river inflows from 0 to 4,000 m³/s and tidal ranges from 0.2 to 1.5 m, implying a wide range of salinity characteristics, including cases with fresh, brackish, oceanic, and hypersaline water. This comparative study indicated the importance of inlet channels and how the water exchange occurs through these channels.

Classification of lagoons

Several systems have been developed to classify lagoons depending on the climatology, inlet *hydrodynamics*, salinity conditions, and geomorphology (e.g., Tagliapietra and Ghirardini, 2006). Kjerfve and Magill (1989) divided

lagoons into choked, restricted, and leaky systems, which refer to the characteristics of the exchange flow with the sea. Choked lagoons include only one inlet channel and the ratio between the inlet cross-sectional area (A_I) and the lagoon surface area (A_L) is small. Thus, the renewal time for the water in the lagoon tends to be long and the exchange flow controlled by riverine processes. A leaky lagoon has several inlets and a larger ratio A_I/A_L with the tidal flow typically dominating the exchange between the lagoon and the sea. Restricted lagoons constitute the intermediate case between choked and leaky lagoons.

Carter (1995) also classified lagoons based on the flow characteristics, but used the typical inflow (Q_{in}) and outflow (Q_{out}) rates through the inlet as the main parameters for distinguishing between different types of lagoons. Three cases were identified, namely, $Q_{in} = Q_{out}$, $Q_{in} > Q_{out}$, and $Q_{in} < Q_{out}$. The case where inflow and outflow is the same corresponds to lagoons where tidal exchange dominates, whereas $Q_{in} > Q_{out}$ prevails for hypersaline lagoons where evaporation is a significant component in the water budget for the lagoon. Hypersaline lagoons are common along low-latitude arid coasts. The third case ($Q_{in} < Q_{out}$) occurs when there is a significant relative contribution from river runoff to the lagoon.

Basic mechanisms for water exchange

The physical and environmental conditions in the lagoon are primarily determined by the water exchange with the sea. This exchange includes a number of components that are of varying relative importance, not only between different lagoons, but also over time (e.g., the presence of annual cycles). Main components defining the water exchange is the tidal flow, river flow, direct surface runoff, wind-induced *circulation*, wave-driven currents, and evaporation. In many lagoons, the tidal and river flows are most important for the water exchange and the water quality in the lagoon. An important quantity defining the water exchange due to the tide is the tidal prism (P), which is the volume of water that is exchanged during a tidal cycle (i.e., the volume of water that flows in and out between high and low tide; O'Brien, 1931). It has been shown that the inlet cross-sectional area at equilibrium conditions, as well as different morphological features such as bars and shoals that form around the inlet, may be related to P (Jarrett, 1976; Walton and Adams, 1976).

The simplest type of mathematical model for determining the water exchange includes only tidal flow (Q_I) and river flow (Q_R), neglecting spatial water level differences in the lagoon and treating it as a homogeneous water body. This type of model was first proposed by Keulegan (1967) and it includes two governing equations, namely, water volume conservation for the lagoon and an energy (or momentum) equation for the inlet. The model contains two unknowns, the water level in the lagoon and the velocity through the inlet, whereas the river inflow and the water level variations in the sea are input quantities.

The conservation equation expresses that the change in the lagoon volume is a result of the inflow due to the tide and river discharge:

$$\frac{d}{dt}(A_L \eta_L) = Q_I + Q_R$$

where A_L is the lagoon surface area and η_L is the lagoon water level. The velocity through the inlet may be obtained from the energy equation between the ocean and the bay:

$$\eta_o = \eta_B + k_f \frac{u_I |u_I|}{2g}$$

where η_o is the ocean water level, k_f is a loss coefficient for the inlet, including entrance, exit, and frictional losses. The flow through the inlet is given by $Q_I = u_I A_I$, where A_I is the inlet cross-sectional area, and inflow to the bay is taken as positive. If there is no tide, the flow at equilibrium through the inlet is equal to the river flow ($Q_I = -Q_R$). In general, it is not possible to find an analytical solution to these two equations, but a numerical approach must be taken.

To spatially resolve the flow field inside the lagoon requires more advanced models (e.g., Fischer, 1981; Buttolph et al., 2006). Such models employ the momentum equations together with the volume conservation equation, often using a depth-averaged description since lagoons tend to be shallow and well mixed through the water column. In a depth-averaged model the local water depth and velocities in two coordinate directions are the unknowns. If density-driven flows are of importance for lagoon *circulation*, the flow equations have to be supplemented with equations describing heat or salt transport depending on whether the density differences are due to temperature or salinity, respectively.

Lagoon mixing and residence time

Lagoons are typically recipients for a wide range of pollution discharges and it is useful to quantify the rate at which the polluted water is renewed. A common quantity for characterizing the water renewal in a lagoon is the residence time T_L , which is the time it takes to replace the entire water volume in the lagoon (V_L) with regard to the exchange flow. If only tidal exchange exists then $T_L = V_L/(P/t_T)$, with t_T being the tidal period, whereas if river flow is present $T_L = V_L/(P/t_T + Q_R)$. Although useful, the residence time is a simplistic measure, assuming no mixing between the new water coming into the lagoon and the polluted water, which in many cases does not properly describe the mixing processes. An alternative approach to assess the environmental conditions in the lagoon is through a box model, in which the lagoon water is taken to be instantaneously and uniformly mixed.

A box model involves a mass balance for the lagoon with regard to a certain pollutant, where the lagoon is considered to be one unit with no resolution in space. However, the quantities describing the lagoon are allowed to

vary in time (e.g., flow rate, volume, area, concentration). The mass balance is written for the pollutant under study, and the water flows and volumes are determined through a Keulegan-type model, as described in the previous section. A simple system of equations for a lagoon that is exchanging water with the sea, including river flow, is given by:

$$\frac{d}{dt}(cV_L) = Q_I c_I + Q_{RCR} \quad Q_I > 0$$

$$\frac{d}{dt}(cV_L) = Q_{RCR} - c(Q_I + Q_R) \quad Q_I < 0$$

where t is the time, c the concentration in the lagoon, c_I the concentration in the inflowing sea water, and c_R the concentration in the river water. Note that the outflow will always have the concentration c (after complete mixing in the lagoon) and inflow is taken to be positive. Tidal inflow periods have to be separated from tidal outflow periods.

For a typical lagoon that is exchanging water with the sea only, having no river inflow and neglecting evaporation, and looking over a longer time period, the inflow equals the outflow and there is no change in the water volume in the lagoon. However, the mass balance for a pollutant typically implies changes in the mass of pollutant in the lagoon since c and c_I will have different values (the inflow will have water with a different concentration than the outflow). After these simplifications, the mass balance for the pollutant may be expressed as:

$$\frac{d}{dt}(cV_L) = \bar{Q}_I c_I - c\bar{Q}_I$$

where $\bar{Q}_I (= P/t_T)$ is the average exchange flow through the inlet. Since the lagoon water volume is constant, the equation may be solved to yield:

$$c(t) = c_i \exp\left(-\frac{t}{T_L}\right)$$

where c_i is the initial concentration at time $t = 0$ in the lagoon (e.g., after a pollution release) and $T_L = V_L/\bar{Q}_I$ (residence time). This solution may be used to estimate how long it will take for the concentration of a certain pollutant to decrease to, for example, $1/10 (= c/c_i)$ of its initial concentration due to the water exchange with the sea. Thus, a measure of the water exchange and its impact on the lagoon environmental conditions may be obtained.

An alternative approach to the box model for simulating the water quality in a lagoon is the advection-diffusion (AD) equation (Fischer, 1981). The AD equation describes the spatial and temporal variation in the concentration of a specific pollutant taking into account the main transport and mixing processes such as advection and diffusion (see *Mixing in Lakes*). Also, sources and sinks that add or remove, respectively, material from the lagoon can be included in the AD equation.

Inlet morphology and closure

The water exchange through an inlet typically induces sediment transport into the lagoon during flood tide and out toward the ocean during ebb tide. Simultaneously, on most coastlines with lagoons, waves generate longshore sediment transport that is interrupted by the inlet flow. The interaction between the transport due to the inlet flow and the waves creates morphological features of different types that in turn affect the flow conditions around the inlet. If the longshore transport is large compared to the inlet transport capacity, the inlet cross-sectional area may decrease, which reduces the water exchange. Also, the inlet can migrate alongshore and even close under strong relative longshore transport. Inlet migration (and closure) greatly impacts the water exchange and environmental conditions in the lagoon. In different parts of the world, for example, Australia, Japan, and Sri Lanka, inlets may seasonally close as waves and river runoff greatly vary over the year. Typical features of the seasonally closed inlets are that they occur in micro-tidal, wave-dominated coastal environments where the seasonal stream flow and wave climate variations are large (Ranasinghe and Pattiaratchi, 1999).

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Cross-references

Circulation Processes in Lakes
 Estuarine Hydrology
 Hydrodynamics and Circulation of Fjords
 Hydrodynamics of Very Shallow Lakes
 Mixing in Lakes
 Sedimentation Processes in Lakes
 Stratification in Lakes

CYANOBACTERIA (BLUE-GREEN ALGAE)

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Introduction

Cyanobacteria (blue-green algae) occur naturally in fresh-water environments including lakes, reservoirs, ponds, and slow-flowing rivers and estuaries. Under enhanced conditions, the cyanobacteria may proliferate and become an unsightly and often poisonous bloom. According to Reynolds (1987), cyanobacterial blooms have done more to give eutrophication its bad name than any other consequence of lake enrichment. The most common bloom-forming genera of cyanobacteria include *Microcystis*, *Anabaena*, *Nodularia*, and *Oscillatoria*.

Biological characteristics

Cyanobacteria are photosynthetic organisms and as such require light (400–700 nm wavelength) and a supply of inorganic carbon to grow. The photosynthetic rate is also affected by nutrient level (particularly phosphorus), water temperature, and water chemistry. For *Microcystis*, the maximum photosynthetic rate of 28.9×10^{-6} (mol C) (mol cell C)⁻¹ s⁻¹ at 20°C is achieved at a photon flux of 753×10^{-6} mol photon m² S⁻¹ (Reynolds, 1990). Certain cyanobacteria such as *Oscillatoria agardhii* are able to increase their photosynthetic efficiency in persistent low light (Reynolds, 1990). The optimum water temperature range for cyanobacterial growth is 25–35°C (Reynolds and Walsby, 1975); blooms generally occur in hard water (Pearsall, 1932) within a pH range of 7.5–9.0 (Kratz and Myers, 1955; Brock, 1973).

The maximum growth rate of *Microcystis* at 20°C is 5.5×10^{-6} S⁻¹ (Reynolds, 1990). If photosynthetic production is greater than this figure, then surplus carbohydrate is stored as ballast. An excess carbon production of 9×10^{-6} (mol C) (mol cell C)⁻¹ s⁻¹ will increase cell density by 1.62×10^{-3} kg m³ s⁻¹. In darkness, stored carbohydrate is used to meet respiratory demand (0.55×10^{-6} [mol C] [mol cell C]⁻¹ s⁻¹),

resulting in density loss. A resultant characteristic of bloom-forming cyanobacteria is that their density varies diurnally above and below that of water (998.2 kg m⁻³ at 20°C), resulting in oscillatory vertical migration patterns. If sufficient density is lost, then the cyanobacteria may migrate to the lake surface and form a concentrated bloom at or near the shoreline. This process is aided by the presence of rigid gas vesicles that give the cyanobacteria additional buoyancy. In some genera such as *Anabaena*, collapse (due to turgor pressure) and light-mediated synthesis of gas vesicles also contribute significantly to density change (Walsby, 1988).

Potential problems

A surface bloom of cyanobacteria may persist if there is a shortage of carbon. Without carbon, photosynthesis cannot occur, meaning that “ballast” accumulation is not possible and the bloom does not sink. Under these conditions, or if the bloom has been transported by wind currents to the shoreline, the bloom may become accessible to water body users. This is potentially dangerous because about 70% of blooms release toxins that can kill animals and cause illness in humans. Exposure to toxins can also cause bioaccumulation in the tissues of fish and shellfish and indirectly affect other organisms through the food chain (Antoniou et al. (2005). The problems and occurrence of toxic cyanobacterial blooms have been reviewed regularly (e.g., NRA, 1990; Chorus and Bartram, 1999; Briand et al., 2003).

In 1996, 100 dialysis patients in Caruaru, Pernambuco State, Brazil, developed acute liver failure apparently caused by intravenous exposure to water supplied from a bloom-affected supply reservoir (Azevedo et al., 2002). Subsequently, in 2000, Brazil incorporated cyanobacteria and cyanotoxin parameters into their drinking water regulations. However, worldwide, national implementation of regulations for cyanobacteria in drinking or recreational waters has been patchy. In the EU, the 2006 Bathing Waters Directive includes direction on the management of “accumulations” of cyanobacteria.

Problem cyanobacterial blooms are not isolated geographically; it is a worldwide water-quality problem that may increase as climate change makes more water environments suitable for cyanobacterial growth. Pearl and Huisman (2009) note that future climatic change scenarios predict rising temperatures and enhanced vertical stratification of aquatic environments which favor harmful cyanobacterial blooms in eutrophic waters.

Future management strategies should consider the impact of global warming on the distribution and growth of problem blooms as well as seeking amelioration through integrated catchment management policies to reduce eutrophication. Artificial mixing devices installed in water bodies can reduce growth by altering the underwater light environment; in some cases, however, this may promote accelerated growth of diatoms and green algae. Short-term solutions such as chemical algicides should be avoided as application may be detrimental to

desirable flora and fauna and may cause a large pulse of growth-promoting nutrient and toxin to be released at once.

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Cross-references

[Light and Primary Production in Lakes](#)
[Nutrient Balance, Light, and Primary Production](#)

D

DAM FAILURES: IMPACT ON RESERVOIR SAFETY LEGISLATION IN GREAT BRITAIN

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Introduction

“Every dam, regardless of its size, is in some degree a potential menace to everything below it. There is nothing so relentless in its immediate destructiveness, so uncontrollable and deadly as a huge volume of water suddenly released.” This warning, which was given at a symposium in New York on the public supervision of dams (Hinderlider, 1932), forms a necessary reminder that although reservoirs have provided immense benefits to mankind, as with all human progress, there is a price to be paid. Part of that price is the potential hazard of a dam breach when the uncontrolled release of the impounded water can cause enormous property damage, injury, and death. In 1930, the year that the New York symposium was held, comprehensive reservoir safety legislation was introduced into Great Britain in the form of the Reservoirs (Safety Provisions) Act.

British reservoir safety legislation applies to “raised reservoirs,” that is to say it applies where artificially created bodies of water are impounded above the level of the surrounding ground. The legislation does not apply to naturally formed bodies of water such as lakes and lochs, nor does it apply where fluids other than water are impounded. The scope of the legislation is restricted to “raised” reservoirs since reservoirs formed by digging a basin in the ground rather than by building a dam are not normally a threat to public safety. Before considering dam failures and their impact on the development of

safety legislation, the history of dam construction in Great Britain and the current population of dams are briefly reviewed.

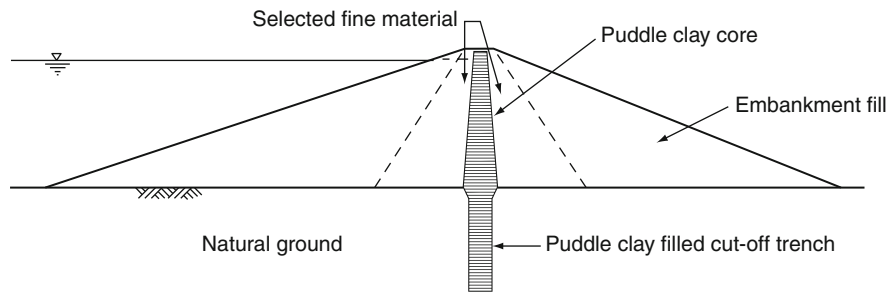
Reservoir construction in Great Britain

Reservoir construction has a long history in Britain, and the 70-m-long, 6-m-high earth embankment which forms the “Great Weir” near Alresford in Hampshire was built in about 1200 AD. It has been suggested that the reservoir, which originally covered 80 ha but is now much reduced in extent, formed part of navigation works on the River Itchen, but it is more likely that it was just a fish pond. During the Middle Ages, power to drive water wheels for mills was one of the principal objectives of constructing dams and weirs, and in the seventeenth century, many weirs were built to improve inland navigation.

From the middle of the eighteenth century, it became fashionable for the owners of country estates to have their grounds landscaped, sometimes involving earth moving on a large scale. Capability Brown, the best known of the landscape gardeners of that time, built many small embankment dams, typically 6 m high, to form “lakes” in the grounds of these country estates. In contrast to the earlier mill dams, these lakes were not utilitarian and were formed solely to improve the environment. This has a certain irony in the light of modern environmental opposition to dam construction.

By the end of the eighteenth century, reservoirs were needed to supply the canals being built across the country. The 21-m-high embankment at Todd Brook, west of Whaley Bridge in Cheshire, was the highest late eighteenth century canal dam. Famous engineers, such as Smeaton, Telford, and Rennie were responsible for many canal dams.

Zoning of fill within the embankment represented a major development in embankment dam construction,



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 1 Typical cross section of puddle clay core dam. (After Charles and Watts, 1987.)

and central puddle clay cores became the norm in the nineteenth century. Figure 1 shows a typical cross-section of this type of embankment dam. Puddle clay is not a description of a particular type of clay but refers to the way clay was puddled by a process in which the natural structure of the clay was destroyed by remolding and working in extra water. Puddle clay had already been used as an impermeable surface lining for canals, but its use to form the central core of a dam marked a major improvement in embankment design.

During the first half of the nineteenth century, the demand for unpolluted water supplies to the rapidly expanding industrial towns led to a major increase in reservoir construction. This continued throughout the nineteenth and twentieth centuries, but there was a decline in dam building in the 1980s, and very few large dams are being designed and constructed in the twenty-first century. Before 1900, nearly all the reservoirs constructed in Britain were impounded by embankment dams, with a notable exception in Vyrnwy, a gravity dam built in 1890 to supply water to the city of Liverpool. In the twentieth century, a significant proportion of dams were built of masonry or concrete. Early in the twentieth century, construction work began in the Scottish highlands for the production of hydroelectric power, and these reservoirs are mostly impounded by concrete dams.

Some 80% of the current population of British reservoirs is impounded by embankment dams. The highest dam in Great Britain is the 90-m-high rockfill embankment which impounds Llyn Brianne in central Wales, but most embankment dams are quite small and are so much in harmony with their environment that members of the public may be unaware that the reservoir is anything other than a natural body of water. Trees on the crest of an old embankment dam may well enhance the environment, but they can have a less desirable impact on the security of the embankment as illustrated in Figure 2. Wave erosion is concentrated in the areas between the trees, and the trees could be uprooted during storms, seriously damaging the embankment crest.

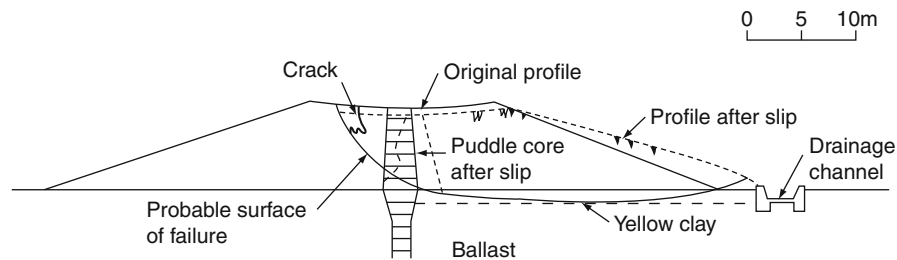
Instability during embankment construction

A significant number of embankment dams have “failed” in the sense that there was a slip in one of the embankment



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 2 Trees on crest of an old embankment dam.

slopes during construction. In July 1937, when 8 m had been completed of the planned 10-m height of the earth embankment for the William Girling storage reservoir at Chingford in Essex, a 90-m-long section of the downstream (outer) slope moved (Cooling and Golder, 1942). The slip surface passed through the central puddle clay core and then followed a path contained within a layer of soft yellow clay in the foundation as illustrated in Figure 3. The Chingford reservoir embankment was one of the first to be built in Britain using what at that time would have been described as “modern earth moving equipment,” and the construction rate was faster than had previously



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 3 Instability during construction of embankment of William Girling reservoir, Chingford, in July 1937. (After Cooling and Golder, 1942.)

been common practice. It seems likely that the development of high pore water pressures in the yellow foundation clay due to rapid loading by the embankment was a major contributory factor in the slope instability. During 1937, two other large embankment dams, Abberton and Hollowell, suffered major slips while under construction.

Most of the cases of instability during construction occurred before the full development and application of modern soil mechanics to the analysis of slope stability, but there has been one notable event in more recent times. At the beginning of June 1984, with embankment construction approaching its maximum height of 35 m, a 400-m length of the upstream shoulder of Carsington dam in Derbyshire slipped some 15 m as seen in Figure 4. The investigation of the events at Carsington made important contributions to the fundamental understanding of the behavior of large earthworks of this type (Potts et al., 1990). In his report to the Secretary of State for the Environment, Coxon (1986) made a number of recommendations including the use of review or advisory panels for major dam construction projects.

While a significant number of embankment dams have suffered slope instability during construction, such slips usually have occurred when there was little or no impounded water and consequently there was no threat to public safety. This was the case at both Chingford and Carsington. However, at Carsington, a major reconstruction of the embankment was needed (Banyard et al., 1992).



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 4 Instability during construction of Carsington embankment dam in June 1984.

Dam failures in Great Britain

It has been noted that it is only when a dam is breached with a consequent uncontrolled release of the impounded reservoir water that public safety is likely to be compromised. Table 1 shows that some 427 lives have been lost in Great Britain in 14 failure events of this nature.

Failure of Bold Venture Lodge in 1848

One of the earliest instances of a dam failure causing a number of deaths occurred on 23 August 1848 when a small puddle clay core embankment dam at Darwen in Lancashire failed by overtopping during a storm. The

10-m-high dam only impounded $20 \times 10^3 \text{ m}^3$ of water, but the failure resulted in the loss of 12 lives. The verdict of the jury at the inquest was that "... all the deaths inquired into occurred by an accidental cause, that cause being the excessive rains of Tuesday night and Wednesday morning, by which the reservoir at Bold Venture Lodge overflowed and washed away the embankment ..."

A few years later, two dam failures in Yorkshire caused much greater loss of life, and the juries at the inquests made much less charitable judgments as to the causes of

Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Table 1 British dam failures causing loss of life (After Charles, 1993)

Dam	Height (m)	Reservoir volume (10 ³ m ³)	Date built	Date failed	Deaths
Tunnel End	9		1798	1799	1
Diggle Moss			1810	1810	5
Whinhill	12	262	1828	1835	31
Brent (Welsh Harp)	7		1837	1841	2
Glanderston				1842	8
Bold Venture (Darwen)	10	20	1844	1848	12
Bilberry	29	310	1845	1852	81
Dale Dyke	29	3,240	1863	1864	244
Rishton				1870	3
Cwm Carne Castle	12	90	1792	1875	12
Malgwyn				1875	2
Clydach Vale				1910	5
Skelmorlie	5	24	1861	1925	5
Eigiau and	10	4,500	1911	1925	16
Coedty	11	320	1924	1925	

the catastrophes, strongly criticizing owners and engineers rather than attributing the deaths to an “accidental cause.” The failures of Bilberry and Dale Dyke were not directly and primarily attributable to extreme floods, and human culpability, doubtless, seemed more obvious.

Failure of Bilberry in 1852

The collapse of Bilberry dam in February 1852 caused 81 deaths and much property damage in the vicinity of Holmfirth in west Yorkshire (Binnie, 1981). Construction of the puddle clay core embankment dam had been beset with problems. Excavation for the cut-off trench began in 1839, and a spring was encountered in the bottom of the trench. The outlet works comprised a masonry culvert which had to cross the puddle-clay-filled cut-off trench, and serious problems soon became apparent: muddy water came through the culvert in 1841, and in 1843, the leakage became worse, and water burst through the culvert. Remedial works were unsuccessful, and large settlements occurred.

It was claimed that between 1846 and 1851, the embankment settled 3 m, eliminating the freeboard. Soon after midnight on Thursday 5 February 1852, the embankment was overtopped and breached during a storm. The reservoir emptied in 30 min. The unsafe state of the dam had been recognized by many of those living closest to it, and the vigilance of these people enabled them to escape the flood that engulfed many of the inhabitants of Holmfirth who lived lower down the valley.

This was the first dam disaster in Great Britain to draw major attention to reservoir safety, and the Home Secretary, Sir George Grey, arranged for Captain R. C. Moody of the Royal Engineers to inspect the remains of the dam and give expert evidence at the

inquest. It would appear that erosion of and through the puddle clay was the cause of the settlement that led to the catastrophe. Captain Moody remarked that a sink-hole in the crest was located above the culvert “and is no doubt due to the washing away of the bad puddling over and above the culvert where it passes through the puddle wall below.”

At the inquest, the verdict of the jury on Friday, February 27, 1852, contained strong criticism of the dam owners, referring to their “gross and culpable negligence,” and pointed to the need for legislation: “We also hope that the legislature will take into its most serious consideration the propriety of making provision for the protection of the lives and properties of Her Majesty’s subjects exposed to danger from reservoirs placed by corporations in situations similar to those under the charge of the Holme Reservoirs Commissioners.”

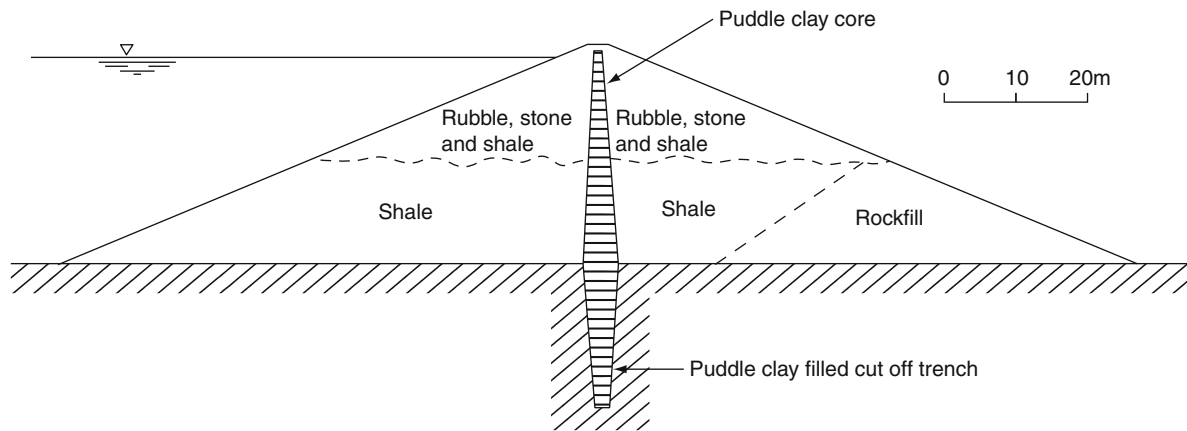
A quick legislative response to the catastrophe was made unlikely by the changes in government that occurred in 1852 (Charles, 2002). It was only when Sir George Grey was Home Secretary again, from 1861 to 1866, that he was able to introduce legislation in response to the Bilberry failure. There were nine clauses in the Waterworks Clauses Act of 1863 on the security of reservoirs. Any interested person could make a complaint to two justices of the peace that a reservoir was in a dangerous state. The justices had powers to order the lowering of the reservoir and the execution of works to remove the cause of the complaint.

Failure of Dale Dyke in 1864

The Dale Dyke dam in south Yorkshire failed during first filling of the reservoir in March 1864. Construction work on the 29-m-high puddle clay core embankment dam started in January 1859; the deep puddle-clay-filled cut-off was completed in 1861, and the embankment was finished by April 1863. The cross-section of the embankment in Figure 5 shows that the puddle clay core was unusually thin. Impounding commenced in June 1863, and by March 10, 1864, the water level was 0.7 m below the crest of the weir. In the late afternoon of the following day, a crack was observed along the downstream slope near the crest of the dam. An attempt was made to blow up the overflow weir, but before this was achieved, the dam breached on the night of Friday, March 11, 1864, at 11.30 p.m.

The reservoir, which was close to the village of Bradfield, was far larger than Bilberry, and the catastrophe claimed 244 lives in the vicinity of Sheffield. This is the most serious dam failure that has occurred in Great Britain and has a strong claim to be regarded as the country’s worst civil engineering disaster. The Home Secretary, Sir George Grey, appointed two civil engineers, Robert Rawlinson and Nathaniel Beardmore, to report on the “failure and bursting” of the reservoir embankment.

A leader in *The Times* on 17 March 1864 argued that those threatened by reservoirs could not be expected to defend themselves and needed protection. There was pressure for a government inspectorate, and the verdict of the



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 5 Cross section of Dale Dyke dam. (After Binnie, 1981.)

jury at the inquest on Thursday 24 March referred to the lack of engineering skill and inadequate attention to the construction of the works and recommended that: "... the Legislature ought to take such action as will result in a governmental inspection of all works of this character; and, that such inspections should be frequent, sufficient, and regular."

In their report to the Home Secretary, Rawlinson and Beardmore (1864) were critical of both the design and the construction of the dam. They believed that failure was most likely to have been caused by leakage from a fractured outlet pipe, but the design and construction of the embankment was also criticized: "... the puddle-wall is much too thin, and the material placed on either side of it is of too porous a character, ... No puddle-wall should ever be placed betwixt masses of porous earth, as puddle, under such conditions, will crack, and is also liable to be fractured by pressure of water."

However, Rawlinson and Beardmore did not endorse the jury's recommendation for government inspection because: "Any approval of plans or casual inspection of waterworks embankments cannot ensure ultimate safety in such works. The responsibility must remain, as at present, with the engineer and persons immediately connected with the works. Magistrates have jurisdiction under clauses inserted in recent Waterworks Acts."

The Waterworks Bill 1865/1866

On 23 February 1865, Sir George Grey announced that legislation was being prepared. The bill was referred to a select committee of the House of Commons, which reported on 23 June 1865. While emphasizing that it did not intend to diminish the responsibility of the owners or operators ("undertakers") of waterworks to pay damages, the Committee made the following recommendations:

- When it is proposed to construct a large reservoir, the undertakers should submit to the appropriate government department plans and sections of the reservoir site

and the proposed works, together with descriptions of the mode of construction.

- The government department should send a competent engineer to inspect and report on the works that are to be constructed.
- When the reservoir is completed, the undertakers should give due notice to the government department, and the reservoir should not be filled with water until the specified time has expired.
- Adequate supervision over all large reservoirs should be maintained by the government department, and competent engineers should be sent to inspect and report on such reservoirs from time to time.

A new bill was introduced in parliament in 1866, largely following the recommendations of the Select Committee and including a clause imposing strict liability. It was restricted to reservoirs impounding over a million cubic feet of water ($28 \times 10^3 \text{ m}^3$). However, the Waterworks Bill of 1866 ran out of time, and following a change in government, in February 1867, it was announced in parliament that there was no intention of reintroducing the bill.

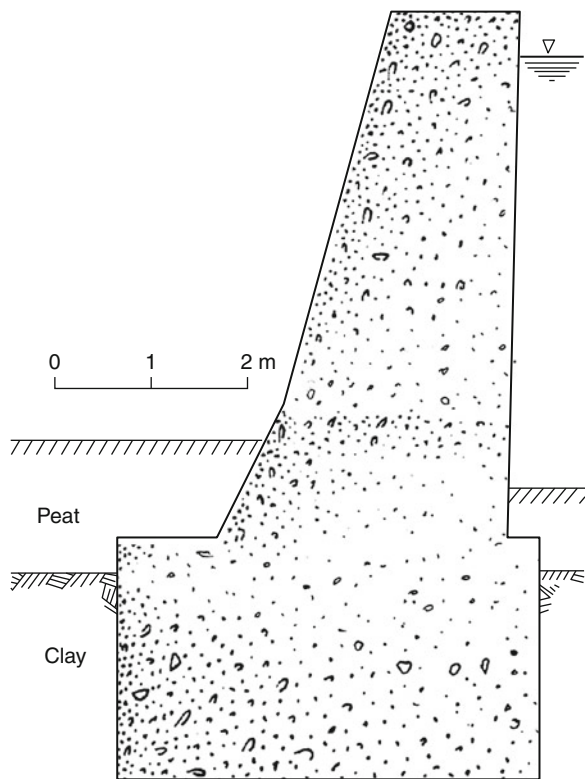
Failures of Skelmorlie and Eigiau/Coedty in 1925

Sixty years after the Select Committee made its recommendations, two further reservoir failures occurred, the first in Scotland and the second in Wales. Following heavy rainfall, the Skelmorlie lower reservoir in south-west Scotland failed at 2 p.m. on Saturday 18 April 1925. The floodwater, which was probably sufficient to overtop the embankment, was augmented by water from a quarry, which having partially filled due to a blocked culvert, suddenly emptied when the blockage cleared. The embankment was breached over a 9-m length, and the reservoir emptied in 15 min. Five people were killed in the village of Skelmorlie. The failure was attributed to a grossly deficient overflow and inadequate freeboard, and the verdict of the jury at an inquiry held at Kilmarnock

Sherriff Court was that: “The disaster was caused by absence of any regular skilled supervision and inspection.”

An even more serious event occurred 6 months later in Wales. The small mass concrete gravity Eigiau dam, which had been built between 1907 and 1911 and which impounded a reservoir with a volume of $4.5 \times 10^6 \text{ m}^3$, breached at 8.45 p.m. on Monday, November 2, 1925. At the location of the failure, the structure is only 5 m high as shown in the cross-section in Figure 6. The failure was caused by the blowout of a 10-m-long section of the dam wall; poor concrete and an inadequate foundation depth were contributory factors in the failure. An arch of concrete remained above the breach. Some $1.5 \times 10^6 \text{ m}^3$ of water was discharged through the breach in the hour following the failure, lowering the reservoir by 1.5 m.

The Coedty embankment dam, which was situated 2.5 miles downstream of the Eigiau dam, only impounded $0.3 \times 10^6 \text{ m}^3$ of water, and the water flooding in from the Eigiau reservoir filled the almost full Coedty reservoir within minutes. The dam was overtopped, and the concrete core wall collapsed. A wave of water and mud hit the village of Dolgarrog at 09.15 p.m. Providentially, most of the villagers were watching the weekly film show in the Assembly Hall, situated on high ground. However, ten adults and six children died in this disaster.



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 6 Cross section of Eigiau dam at failure location. (Based on Engineering News-Record, 1926.)

Technical evidence at the inquest was given to the effect that the foundation of the Eigiau dam had not been sufficiently deep. The jury returned a verdict of accidental death: “caused by the bursting of the dam under the wall in consequence of the wall lacking a proper foundation.” The coroner’s jury recommended regular government inspection.

The Coedty embankment dam was repaired, but the Eigiau concrete dam was not rebuilt; Figure 7 is a recent photograph of the breach. The concrete arch, which initially bridged the ruptured area, was blown up, facilitating the post-failure inspection of the cross-section on either side of the breach.

Following this failure, a leading dam engineer, Edward Sandeman, wrote to *The Times*, and his letter was published on Friday, December 4, 1925. It commenced: “In view of the loss of life following upon the failure of the dams of reservoirs in Scotland and North Wales recently, I beg to call your attention to the report made by the Select Committee on the Waterworks Bill 1865 (Sessional Paper 401), after they had considered the evidence as to the failure of the earth embankment of the Bradfield Reservoir on March 11, 1864, when 245 lives were lost.”

Sandeman commented that it was “unfortunate” that some such control as was then suggested had not been brought into effect and pointed out that there was a vital need to investigate the ability of the reservoirs of the country, firstly, to withstand the pressures to which they are subjected in normal operation and, secondly, to assess whether their overflows were of sufficient capacity to deal with floods caused by the exceptionally heavy rainstorms which had occurred in the previous 15 years.

Having made reference to earth embankment dams which had sunk in the center to such an extent that they were in a dangerous condition and to overflows which had been interfered with and altered to a dangerous extent, Sandeman concluded that “These instances alone are sufficient to show that inspection of existing reservoirs is necessary. In the interests of the public safety it is of importance that the matter should receive attention without delay.”

Reservoirs (Safety Provisions) Act 1930

Government legislation on reservoir inspection was implemented, but not without further delay! 5 years after Edward Sandeman’s letter was published in *The Times* and following a change of government in 1929, the Reservoirs (Safety Provisions) Act 1930 became operative on 1 January 1931. It was described as: “An Act to impose, in the interests of safety, precautions to be observed in the construction, alteration, and use of reservoirs, and to amend the law with respect to liability for damage and injury caused by the escape of water from reservoirs.” Some of the main requirements of the legislation, which was applicable to reservoirs holding more than five million gallons ($22.7 \times 10^3 \text{ m}^3$), were as follows:

- Design and supervision of construction by a qualified civil engineer



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 7 Breach in Eigiau concrete gravity dam.
(Reproduced by permission of Dr Paul Tedd.)

- Reservoir not to be filled until a qualified civil engineer has issued a certificate
- Inspection by a qualified civil engineer at intervals of not more than 10 years
- Undertakers (owners or operators) to keep a record of water levels, leakages, and settlements

A qualified civil engineer was defined as a civil engineer who was a member of a panel constituted for the purposes of the Act. With the advice of the President of the Institution of Civil Engineers, two panels of qualified civil engineers were formed: a panel of engineers qualified to design and supervise construction and inspect all reservoirs to which the Act applied and another panel of engineers qualified only to inspect reservoirs.

In 1946, a four-panel system was introduced. Engineers in all four panels could act as the construction engineer as well as inspect reservoirs, the differences in the panels now related to the type of reservoir: panel I was for all reservoirs and the other three panels were restricted to various types of non-impounding reservoirs. Admission to the panels was at the discretion of the Home Secretary after consultation with the President of the Institution of Civil Engineers who initially set up a small informal advisory committee. It was only in 1965 that a special committee was formally constituted by the Institution for this purpose.

Reservoirs Act 1975

Since the implementation of the 1930 Act, there have been no dam failures in Great Britain causing loss of life, and in view of the link between catastrophic failures and the

demand for legislation, further legislation might have seemed unlikely. Nevertheless, failures and serious incidents continued to occur, and it was known that many other countries were reviewing their regulations. Against this background in 1964, the Institution of Civil Engineers formed a committee which in 1966 published recommendations for amending the law on reservoir safety (Institution of Civil Engineers, 1966).

The Reservoirs Act 1975, which received Royal Assent on 8 May 1975, repealed the Reservoirs (Safety Provisions) Act 1930 and re-enacted the legislation on reservoir safety in a strengthened and more effective form. The content of reservoir safety legislation was greatly expanded by the new Act. Although it was expected that most of its provisions would be brought into force some time before the end of 1975, the Act was only implemented between 1983 and 1987.

The 1975 Act applied to “large raised reservoirs,” that is, reservoirs designed to hold or capable of holding more than 25,000 m³ of water above the natural level of any part of the land adjoining the reservoir. This volume is about 10% greater than the five million gallons specified in the 1930 Act. The Act together with associated Statutory Instruments provided a legal framework within which qualified civil engineers make technical decisions relating to the safety of reservoirs. In effect, the legislation imposed a system of safety checks on reservoir construction and operation.

The 1975 Act kept the same approach to reservoir safety as the 1930 Act in maintaining the panel system of qualified civil engineers but created the new role of supervising engineer. The Act recognized four types

of persons or organizations with distinct functions and responsibilities:

- Undertakers with duties as owner or operator
- Enforcement authorities to ensure compliance with legislation
- Qualified civil engineers to advise on safety
- A government department as legislator

While the 1975 Act embodied most of the recommendations of the 1966 report of the Institution of Civil Engineers committee, there were some significant exceptions: a requirement for undertakers to have third-party insurance was not introduced and the Act was not extended to structures storing liquids other than water. Central control of records and enforcement was not introduced, and enforcement was delegated to local government. A major step toward the central control of enforcement of the Act was taken when the Water Act 2003 transferred the role of enforcement authority in England and Wales from 136 local authorities to the Environment Agency. This transfer took place in October 2004.

Flood and Water Management Act 2010

Despite the excellent record of public safety since reservoir safety legislation was introduced and the undoubted fact that subsequent legislative changes have improved reservoir safety, serious incidents have continued to occur (Wright, 1994). During a flood on 25 June 2007, a serious incident at Ulley puddle clay core embankment dam near Rotherham in south Yorkshire threatened public safety. Although the dam did not breach and there was no uncontrolled release of reservoir water, the failure of the stepped masonry spillway and the associated erosion of the downstream shoulder fill shown in Figure 8 resulted in precautionary measures in which the M1 motorway

was closed for 2 days and 1,000 people were evacuated, although some of these were evacuated as a result of flooding already being experienced (Hinks et al., 2008). A post-incident review of this serious incident identified three areas where action was needed (Mason and Hinks, 2009):

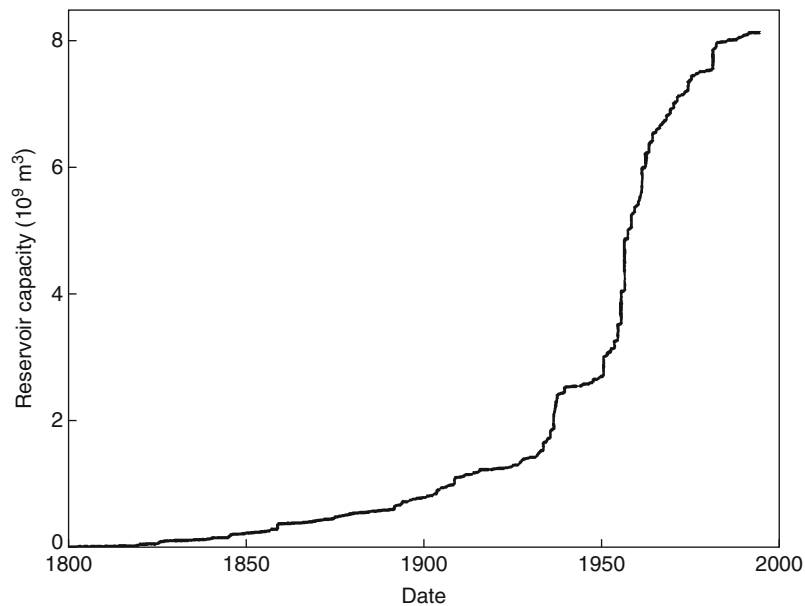
- Development of a better understanding of the defective behavior which caused the incident
- Improvement of preparedness for emergency situations
- Enhancement of a reservoir surveillance culture

In his review of flooding, Sir Michael Pitt (2008) recommended that “The Government should implement the legislative changes proposed in the Environment Agency biennial report on dam and reservoir safety through the forthcoming flooding legislation.” These Environment Agency proposals included moving to a risk-based definition for reservoirs within the ambit of legislation and mandatory post-incident reporting.

While maintaining the panel system of qualified civil engineers for the inspection and supervision of reservoirs, the Flood and Water Management Act 2010 includes provisions for a new risk-based approach to reservoir safety. The new legislation means that a substantial number of small dams which are not considered to be high risk, since failure would have no serious consequences for public safety, can be removed from the onerous requirements of the safety regime. This change is appropriate since a preliminary estimate indicated that about one third of the total population of reservoirs within the ambit of the 1975 Reservoirs Act may not present a significant threat to lives in the event of a dam breach (Charles and Tedd, 2000). Much more importantly, small reservoirs which could endanger human lives, but which were outside the scope of the 1930 and 1975 Acts, can be brought into the new



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 8 Erosion of downstream slope adjacent to overflow channel at Ulley embankment dam in June 2007. (Reproduced by permission of Mr J R Claydon.)



Dam Failures: Impact on Reservoir Safety Legislation in Great Britain, Figure 9 Progress of reservoir construction in Great Britain. (Based on data in *Register of British dams*, Building Research Establishment, 1994.)

safety regime which may require all owners of a reservoir impounding more than 10,000 m³ of water to register their reservoir.

The Flood and Water Management Act gained Royal Assent on April 8, 2010, but in May, there was a change in government. At the time of writing, it is not yet clear in what stages and on what time scale the new legislation will be implemented. The Act extends to England and Wales; separate legislation has been drafted in Scotland.

Concluding remarks

The development of British reservoir safety legislation over a period of more than a 100 years has largely been in response to failures and serious incidents. Under this legislation, the ultimate responsibility for reservoir safety lies with owners, and there is a marked absence of direct control by central government. The legislation provides a framework within which independent qualified civil engineers make technical decisions relating to reservoir safety, and great reliance is placed on the competence of these engineers. The legislation contains no technical standards, and appropriate technical guidance has been provided in the form of engineering guides which are listed in "A Guide to the Reservoirs Act 1975" (Institution of Civil Engineers, 2000).

Half the reservoirs which came within the 1975 legislation were built prior to 1900, and Figure 9 shows how over the last 200 years the total storage capacity of British reservoirs has steadily increased, particularly since 1950. With the massive increase of impounded water, there is a much greater potential for loss of life and damage resulting from dam failures, and with an ageing population

of embankment dams, there is no room for complacency, despite the fact that since the 1930 Act came into force no deaths have been reported due to dam failures and the safety record since 1930 has confirmed the general soundness of the British approach to reservoir safety legislation.

The legislation enacted in 2010 introduces a risk-based regime for reservoir safety in contrast to previous legislation where the criterion for a reservoir to come within the ambit of safety legislation was solely based on the impounded volume of the reservoir (five million gallons in the 1930 Act and 25,000 cubic meters in the 1975 Act). Despite this sensible change, future reservoir safety will continue to largely depend on maintaining the professional and technical standards of qualified civil engineers, and continuing vigilance at each reservoir will require appropriate levels of surveillance and, where necessary, upgrading old dams to acceptable current standards.

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Cross-references

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[Dams, Flood Protection, and Risk](#)

DAMS AND RESERVOIRS IN MACEDONIA

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Introduction

The Republic of Macedonia is located in the central part of the Balkan Peninsula, in the area between 20°27' and 23°01' longitude East (East from Greenwich) and 40°51'

and 42°21' latitude North. It covers an area of 25,713 km² with a population of about two million inhabitants. Its mountain relief, vast valleys, and numerous long and narrow ravines distinguish the topography of the Republic of Macedonia (RM). The territory of the country is under the influence of the modified Mediterranean type of climate resulting from the Continental, Middle European, and dry Eastern climate influences and the influence of the mountain climate, as well as the secondary factors – relief and elevation. As a result of the climate corridors, the relief in the inland area, and its high latitude, there is a great spatial variability of different climatic parameters: rainfall, temperature, air pressure, winds, low humidity, and other factors significant for the water regime.

For the people in the RM, agricultural production has been, even for ancient times, the basic source of existence. The first agricultural civilization in Europe has been existent on Macedonian land some 10,000 years ago. In order to fight droughts, and at the same time to protect themselves from floods, the farmers associated themselves in different ways. They tried jointly to capture the surface water and convey it to the arable land or to make primitive embankments in order to defend themselves from the destructive power of floods (Dodeva, 1999). After the World War II, special priority was given to water and water management, especially by using artificial reservoirs. At that time, within a relatively short period, plans were elaborated for the water management development, respectively for irrigation, drainage, hydropower, flood control, etc.

Surface water – rivers

According to the hydrographical division, the rivers in the RM belong to three main river basins:

1. The Aegean basin, in which they flow out through the rivers Vardar and Strumica
2. The Adriatic basin, to which they are taken away through the river Crn Drim (Black Drim)
3. The Black Sea basin, through the river Binachka Morava, which extends over a quite insignificant part

The biggest is the catchment basin of the river Vardar, which extends to some 20,525 km² or 80% of the territory of the RM.

Total annual available surface water resources in the RM are assessed as 6,372 billion m³, which lead to about 3,300 m³ per capita annually.

Precipitation

The annual average precipitation in the entire state is approximately 730 mm/year, but it ranges from 380 mm in some parts of Eastern and Central Macedonia, up to 2,000 mm in some mounting regions of Western Macedonia. The distribution of the rainfall is very unfavorable in space and time and relatively small in quantity, as a result of the Continental climate and the

Mediterranean influence. The uneven distribution of the rainfall in time and space results in long dry periods (summer–autumn) and shorter winter periods. On the other hand, there is abundant rainfall between October and December and limited rainfall between March and May. Such a distribution of the precipitations, together with the other meteorological phenomena, categorizes the RM as a semi-arid area.

Water demands

The total water demand in the country is 2,030 million m³ annually. Dominant user of the water is the irrigation with 900 million m³ (46%), then minimum accepted flows with 635 million m³ (28%), follows industry with 275 million m³ (14%), and drinking water supply of the population and tourists with 220 million m³ (12%).

The use of water for electricity production, which is closely connected with the reservoirs, is also very important, taking into account that it is a renewable and adaptable energy resource. Total hydropower potential of the RM is estimated on 5,200 GWh, and currently only 27% or 1,500 GWh is used, with an installed power of 530 MW. Depending on the hydrological conditions, the hydropower covers from 10% to 19% of the total energy demands in the country. The annual production in 2000 was 1,170 GWh; in 2001, 621.5 GWh; in 2002, 755.4 GWh; and in 2003, 1,370 GWh. Among ten existing hydropower plants (HPP) on the large reservoirs, the most important are: Vrutok (27% of total production), Shpilje (24%), Tikves (17%), Globochica (15%), small HPPs (11%), Vrben (3%), and Raven (3%). It is interesting to note that the HPP Vrutok, Raven, and Vrben are units of one cascade system, which is supplied with water from the reservoir *Mavrovo* (Dodeva, 2004).

Dams and reservoirs in the Republic of Macedonia

The construction of dams with reservoirs in the Republic of Macedonia dates from 1938, when the *Matka* arch dam was built located on the river Treska, in the vicinity of Skopje. The purpose of this dam with a 3.55-million-m³ reservoir volume has been electricity production (installed capacity $N_i = 3,2$ MW), and it is still in service. Until now, 20 large dams have been built which enclose impounding reservoirs, Figure 1 and Table 1, as well as around 120 small dams, forming reservoirs with volume lower than 500,000 m³. The golden period for reservoir construction was 1952–1972, when 13 important reservoirs were formed by large dams: *Mavrovo*, with dam height of 54 m; *Globochica* (82.5 m); *Vodocha* (42 m); *Tikvesh* (104 m); *Kalimanci* (85 m); *Shpilje* (101 m); *Turiya* (77.5 m); *Lipkovo* (29.5 m); *Gratche* (29 m); *Mladost* (27 m); *Prilep* (35 m); *Ratevska Reka* (49 m); and *Glaznja* (71.5 m). Up to 1982, four new dams with large reservoirs were commissioned, the largest and most important between them being *Strezevo* ($H = 76$ m), especially important for the region of the city of Bitola. During the last 15 years, the reservoir construction was again intensified, resulting to the finishing of the projects

Kozyak ($H = 114$ m, the highest dam in Macedonia) and *Lisiche* (66 m). Recently, the construction works on the projects *Saint Petka* and *Zletovica* have started. The dams *Kozyak*, *Tikvesh*, and *Shpilje* are the largest projects of this type, enclosing reservoirs with volume range of a half billion m³.

Different kinds of dam sites are presented in the RM concerning the geological, topographical, and hydrological conditions. That is why between the built dams there are both concrete and embankment dams. Most of the large dams with reservoirs – 13 – were constructed of local materials: clay, sand, gravel, and rock, while 6 dams were constructed as concrete arch dams and only 1 as concrete multiple-arch dam.

The stored water is used for meeting the demands for water supply of population and industry, irrigation, production of electricity, flood and erosion control, provision of minimum accepted flows, recreation, and tourism. The total stored volume of water in the Macedonian reservoirs is about 2.4×10^9 m³. The small reservoirs, formed nearly in all cases by earth-fill dams, are built mainly during the last 40 years. Its main purpose is to provide water for irrigation.

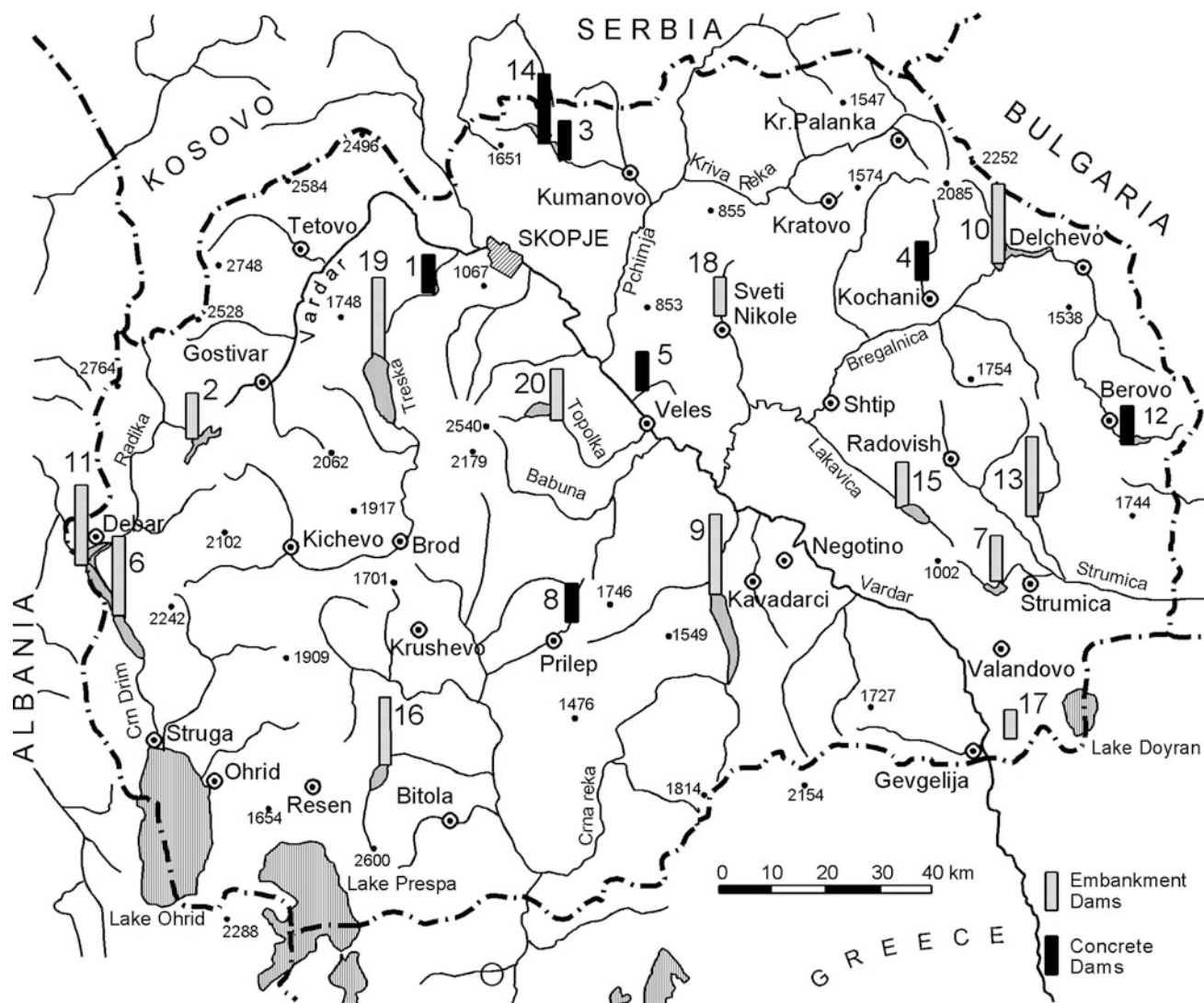
The most important reservoirs formed by large dams in the RM are (Tančev, 2003; Tančev, 2005):

Matka (*St. Andrea*) – the first artificial lake in Macedonia (1938, 3.55 million m³), formed by an arch concrete dam (29.5 m high), located in the exit of the river Treska from a picturesque narrow gorge, Figure 2. All structures, together with the reservoir, are very well adapted to the terrain and to the nature. The purpose of the reservoir is electricity production, with the installed capacity of the power plant of 3.2 MW, not small for the period just before the World War II. After the refurbishment recently done, the installed capacity was doubled. The reservoir serves also for recreation of the citizens of the nearest city Skopje.

Mavrovo – very important lake, at altitude of 1,200 m. a.s.l., formed with the first Macedonian embankment dam, built in the period 1947–1953. The reservoir volume is more than 300 million m³, while the maximum depth is around 50 m. It gains water not only from the own catchments area but also from the adjacent catchments area of the river Radika, through a specially built water-supplying tunnel. It serves mainly for electricity production by means of three power plants (more than 400 million kWh per year) and also for recreation, tourism, and fishing. The mountainous environment surrounding the lake is extremely nice.

Vodocha – built on the river having the same name (1965), with reservoir surface area of 1.94 km² and volume of 26.7 million m³, formed by an earth-rock dam, 44 m high. The purpose of the reservoir is irrigation, but it serves also for fishing and recreation of the citizens of the neighboring town of Strumica.

Prilep – a reservoir with volume of 6 million m³, formed by a unique multiarch buttress dam, 35 m high. The main aim of the reservoir is irrigation of the famous tobacco fields surrounding the town of Prilep.



Dams and Reservoirs in Macedonia, Figure 1 Large dams with reservoirs in the Republic of Macedonia (After Tančev, 2005).

Tikvesh – one of the largest Macedonian reservoirs (total volume 475 million m^3 , length 22 km), formed by an earth-rock dam, 104 m high, built in 1968 on the River Crna, the largest tributary of Vardar. This reservoir, aimed for electricity production and irrigation of the agricultural fields in the central part of Macedonia, is of great importance for the state economy. The lake is rich with different kinds of fish – examples of carps and spearfish up to 100 kg have been caught.

Kalimanci – the largest reservoir in the Eastern Macedonia, with volume of 127 million m^3 , formed by an earth-rock dam 85 m high, damming the river Bregalnica, the most important left tributary of Vardar. This reservoir has a key role in the agriculture of this dry region, irrigating the fertile fields near the towns of Kochani, Shtip, and Sveti Nikole. A small power plant also is in operation.

Shpilje – one of the three largest Macedonian artificial lakes ($V = 520$ million m^3), located on the river Crn Drim, near the Albanian border. The river Crn Drim flows out from large natural Ohrid Lake. By means of a simple regulating structure, Ohrid Lake is an excellent compensation basin for the two downstream power plants with artificial reservoirs: Globochica ($V = 58$ million m^3) and Shpilje. The mean annual electricity production of Shpilje plants is around 300 million kWh. The reservoir is rich with fish, mainly carp. With the high dams Globochica and Shpilje, as well as with the three dams on the river Drim in Albania, the migration path of the eels from Ohrid Lake to Sargasso Sea has been broken.

Ratevska Reka – located in the mountainous Eastern region, formed with a double curvature arch concrete dam 49 m high, near the town of Berovo, at an elevation

Dams and Reservoirs in Macedonia, Table 1 Reservoirs in the Republic of Macedonia formed by large dams

Name	River	River basin	Year compl.	C_A (km ²)	A_R (km ²)	V_R (m ³ × 10 ⁶)	Dam type	H_D (m)	L_D (m)	V_D (m ³ × 10 ³)	Purpose
1. Matka	Treska	Vardar	1938	2,000	0.25	3.55	AR	29.5	64	3	HEP
2. Mavrovo	Mavrovska	Crn Drim	1952	321	13.70	357	EAR	54	210	777	HEP, IR
3. Lipkovo	Lipkovska	Vardar	1958	110.1	0.40	2.25	AR	29.5	203	13	IR, WS
4. Gratche	Kochanska	Vardar	1959	87.5	0.19	2.4	AR	29	150	12	WS, IR
5. Mladost	Otoevica	Vardar	1962	97.0	0.84	8	AR	27	73	2.6	IR
6. Globochica	Crn Drim	Crn Drim	1965	3,118	2.70	58	E-R	82.5	196	998	HEP
7. Vodocha	Vodocha	Strumica	1965	75.9	1.94	26.7	E-R	48.7	185	316.8	IR, WS
8. Prilep	Oreovechka	Vardar	1966	49.4	0.54	6	MA	35	408.5	25.5	IR
9. Tikvesh	Crna Reka	Vardar	1968	5,361	14.00	475	E-R	104	338	2,722	IR, HEP
10. Kalimanci	Bregalnica	Vardar	1969	1,100	4.23	127	E-R	85	240	1,389	IR, HEP
11. Shpilje	Crn Drim	Crn Drim	1969	3,941	13.20	520	E-R	101	330	2,699	HEP
12. Ratevska	Ratevska	Vardar	1972	53.6	0.57	10.5	AR	49	194	21.7	WS, IR
13. Turiya	Turiya	Strumica	1972	213	1.50	48	E-R	77.5	417.3	1,978	IR, WS, HP
14. Glaznja	Lipkovska	Vardar	1972	100	0.97	22	AR	71.5	344	168	IR, HEP
15. Mantovo	Lakavica	Vardar	1975	180	4.94	47.5	E-R	37.5	138	261	IR, WS
16. Strezevo	Shemnica	Vardar	1982	125	4.50	112	E-R	76	632	4,300	IR, WS, HEP
17. Paljurci	Luda Mara	Vardar	1982	63.2	0.35	2.9	EAR	21.1	310	185	IR
18. Mavrovica	Mavrovica	Vardar	1982	43.5	0.34	2.8	EAR	24	360	400	WS, IR
19. Kozyak	Treska	Vardar	2004	1,815	14.8	550	E-R	114	300	3,340	R, HEP, WS
20. Lisiche	Topolka	Vardar	2008	133	1.2	23.4	EAR	66	650	3,295	WS, IR

C_A catchments area, A_R reservoir surface area, V_R maximum reservoir capacity, H_D height of the dam above ground, L_D length of dam crest, V_D dam volume, *EAR* earth-fill dam, *E-R* earth-rock dam, *R-F* rock-fill dam, *AR* arch dam, *MA* multiarch, *WS* water supply, *IR* irrigation, *HEP* hydroelectric power, *R* retention

**Dams and Reservoirs in Macedonia, Figure 2** Dam and reservoir *Matka*.

of around 1,000 m.a.s.l. It serves for water supply, irrigation, and recreation.

Turiya – with volume of 48 million m³, closed by means of an earth-rock dam 77.5 m high, enables the water supply of the town of Strumica, as well as irrigation of the

rich surrounding fields. Secondary purposes of the reservoir are electricity production in a small power plant and fishing.

Glaznja – located on the river Lipkovska (the nearest city Kumanovo), formed by the highest concrete dam in

the RM (71.5 m). The reservoir volume is 22 million m³. Commissioned in 1972, it has served for water supply, irrigation, and electricity production (in a small power plant).

Mantovo – a key structure in the frame of the irrigation system, having the same name. The reservoir volume is 47.5 million m³, formed by an earth-rock dam 37.5 m high, very important for the agriculture of the region of Radovich.

Strezevo – a large reservoir (109 million m³), formed by damming the river Shemnica with an earth-rock dam, 76 m high. The reservoir is a part of a modern hydrosystem, aimed for irrigation of more than 20,000 ha of agricultural field in the plain Pelagonija, water supply for the city of Bitola and the adjacent large thermo-power plant, and electricity production in two small power plants.

Kozyak – located some 16 km upstream from the first reservoir built in the RM, Matka (St. Andrea, 1938). Commissioned in 2004, this reservoir is a key structure of the multipurpose scheme with the main task of flood control, with retention storage of 100×10^6 m³. Also, it serves for electricity production (152×10^6 kWh per year), as well as for water supply. The total reservoir volume is 550 million m³, formed by Kozyak Dam, an earth-rock dam, the highest in the RM (114 m above the terrain, 130 m above the foundation). The dam site is narrow, with valley slopes of 1:1 and 1:1.5, respectively. The dam body is built from rock-fill (limestone), taken from the quarry near the dam, while the waterproof element is in the form of slightly inclined core. Due to rather unfavorable geological conditions in the zone of the reservoir, as well as in the dam site (presences of carstified limestone, faults, and so on), extensive grouting works have been performed to reduce the seepage.

Lisiche – with a volume of 23.4 million m³, closed by means of an earthen dam 66 m high, commissioned in 2009. In the first stage, it enables the water supply of the town of Veles. In the second stage, irrigation of the surrounding fields is planned.

Maintenance and operation

The large dams and their reservoirs are operated by different operators depending on the main use of the stored water. The public utility “ELEM” is responsible for operation of the reservoirs the main purpose of which is energy production, while other dams are mainly operated by the public Water Economy Enterprises, Agro-combine, or private Water Organizations. During the whole period of almost 70 years of construction and service of dams and large reservoirs in the RM, there was no serious incident, despite of the chronic lack of funds for maintenance and reparation. Monitoring and surveillance have been performed continually, but a lot of devices are out of use and have to be repaired or replaced.

Environmental impact

The major number of dams and reservoirs were constructed more than 35 years ago, which presents a sufficient period of time for assessment of the

environmental impact. The analyses and the assessment are rather positive due to the location of dams and applied technical solutions. The dams are mainly located in the upstream section of the rivers, in the mountains where there were no populated areas, or significant industrial or economic facilities. With small exceptions, there was no need for large resettlement of the population or facilities. Also, applying appropriate technical measures, the alternative paths were provided for the aquatic species. The situation is similar with the new planned dams. All of them should be constructed in non-populated areas; no significant size of irrigable lands, facilities, or cultural and historical monuments should be flooded; and no specific or protected species would be endangered. The Environmental Impact Assessment Study is a legal obligation as part of the Feasibility Study documentation.

Future plans

According to the national planning documents Water Master Plan and Spatial Plan, more hydropower projects have been planned (all with large dams and reservoirs), the majority of them being: *Sveta Petka*, river Treska, $H = 50$ m, 36 MW, 53 GWh/year (under construction); *Boshkov Most*, river Jadovska, $H = 45$ m, 70 MW, 127 GWh/year; *Chebren*, river Crna, $H = 192$ m, 150 MW, 286 GWh/year; *Gradec*, river Vardar, $H = 42$ m, 55 MW, 252 GWh/year; *Galishte*, river Crna $H = 140$ m, 195 MW, 257 GWh/year; and *Lukovo Pole*, 103 GWh/year.

Two of these reservoirs, *Chebren* and *Galishte*, will serve also for irrigation. To meet the increased demands for different purposes, another large dams with reservoirs are planned, as *Knezevo* (main structure of the multipurpose hydrosystem “Zletovica”), $H = 75$ m (the dam is already finished, the reservoir filling is planned for the Autumn 2011); *Vakuf*, river Kriva Reka (multipurpose); *Razlovci*, river Bregalnica, irrigation; *Konjsko*, river Konjska, irrigation; *Plavaja*, river Plavaja, irrigation; *Buchin* (multipurpose); and *Paligrad*, river Kadina Reka (multipurpose) (Tančev and Petkovski, 2006).

Damming the rivers and forming large reservoirs, two major axioms are always under consideration of dam designers in the RM: The development must respect the principle of sustainability, and the environment has to be protected from possible negative effects. By fully respecting these two major axioms and using our own experience, as well as the experience of the developed countries, the future generations may enjoy the benefits of clean, well preserved, wisely utilized, and planned water resources (Dodeva, 1999).

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Cross-references

[Macedonian Lakes](#)

DAMS AND RESERVOIRS, ROLE

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Introduction

There is no life on earth without water, our most important resource apart from air and land. During the past three centuries, the amount of water withdrawn from freshwater resources has increased by a factor of 35, while the world population by a factor of 8. With the present world population of 6.8 billion still growing at a rate of about 90 million per year, and with their legitimate expectations of higher standards of living, global water demand is expected to rise by a further 2–3% annually in the decades ahead.

Meeting water demand by dams and reservoirs

Freshwater resources are limited and unevenly distributed. We cannot forever try to meet insatiable demands by continuously expanding a supply that has limits. In the high-consumption countries with rich resources and a highly developed technical infrastructure, the many ways of conserving, recycling, and reusing water may more or less suffice to curb further growth in supply. In many other regions, however, water availability is critical to any further development above the present unsatisfactorily low level, and even to the mere survival of existing communities or to meet the continuously growing demand originating from the rapid increase of their population. In these regions, man cannot forego the contribution to be made by dams and reservoirs to the harnessing of water resources.

Storage and release

Seasonal variations and climatic irregularities in flow impede the efficient use of river runoff, with flooding and drought causing problems of catastrophic proportions. For almost 5,000 years, dams have served to ensure an adequate supply of water by storing water in times of surplus and releasing it in times of scarcity, thus also preventing or mitigating floods. In response to enormously increased demand, more than half of ICOLD's registered 39,000 large dams have been built in the past 40 years. They have become an integral part of our technical infrastructure, and throughout the world, they enhance the basis

of life by offering many indispensable benefits. Still more dams will be needed in the future for the adequate management of the world's limited, unevenly distributed, and, in many places, acutely scarce water resources.

The need for dams and reservoirs

The need for dams and reservoirs applies in particular to the developing regions of the world, which account for 70% of the world population, and for no less than 94% of annual population growth. There are one billion people suffering from chronic undernourishment or plain starvation, with between 10 and 15 million children dying of hunger every year. About 1.5 billion people have no access to a reliable source of drinking water, and more than two dozen countries have not enough water to sustain their populations properly. Millions die from water-related diseases every year. The result is an exodus of the impoverished rural populations to the even greater inhumanity of the vast shanty towns surrounding the big cities. Of the 22 cities which will have more than 10 million inhabitants by the end of the century, 18 will be in developing countries.

The need for irrigation

In many countries, increased food production is only possible through improved or increased irrigation. At the present time, about 250 million hectares of land is under irrigation, growing one third of our food on less than one fifth of the world's cultivated area and accounting for almost three quarters of world water consumption. In conjunction with great efforts to develop effective ways of saving water by avoiding losses in the distribution systems and by applying more skillful irrigation techniques, UNDP (the United Nations Development Programme) is aiming at a 3% compound rate of growth in irrigated agriculture to meet the needs of an extra one billion people in the next 10 years. Half of them will be city dwellers with a concentrated drinking water requirement. Since the groundwater reservoirs presently tapped to provide about half of irrigation, drinking, and industrial water supply are already heavily overdrawn in many parts of the world, the only large-scale solution apart from saving water is to increase the share of surface water from storage reservoirs.

The quantity of irrigation water required to produce a crop under reservoir conditions depends on a number of factors, such as the natural rainfall and other climatic conditions, type of crop, length of growing season, method and scheduling of irrigation, and soil properties. Several methods for estimating crop water requirements are in use in different countries, but they are usually suitable only for the condition under which each was developed.

Environmental effects

Environmental effects are of increasing concern in the role of dams and reservoirs. The creation of reservoirs usually has a very important influence on ecology. In the case where the storage volume is large in relation to annual

runoff, eutrophication can have a significant impact on the quality of the water in the reservoir because of long residence times. The reservoir exerts a great influence on the temperature and oxygen content of the release water. The regulation of flow will also change the nature of land use downstream of the reservoir. The increase in water use usually results in an increase in the amount of waste water that may lower the quality of water in the receiving river.

Changes of this nature are of major concern. However, reservoirs also cause changes that have beneficial effects. In many cases, the environment in the vicinity of reservoirs and downstream has been greatly improved by providing recreation, esthetic, ecological, and health benefits. It is of primary importance to assess continuously all environmental effects of storage reservoirs and to provide monitoring facilities for measuring environmental factors both before and after construction.

Purposes to be served by dams and reservoirs

In the usual scheme of development for a river basin, all flow which can be suitably regulated is utilized. The available water is divided among requirements in accordance with a system of priorities. Requirements with highest priority are satisfied at all times if possible, while others are served only when sufficient water is available.

Criteria used in the design and operation of dams and reservoirs are usually based on obtaining the maximum net benefits with the resources invested in the project. A design to meet the full demand need not always be the most desirable alternative. Supplies can only be made available at a unit cost which usually increases as the supply grows and can, at some point, exceed the loss resulting from the reduced efficiency of an undersupplied facility. Conflicts can also occur among the various intangible aspects arising, on the one hand, by making supplies available and, on the other, by curtailing demands. It is the objective of water resources management to seek an optimal balance between water supplies and demands by quantifying, to the extent possible, the consequences of trade-offs between the conflicting tendencies on the basis of cost-benefit studies and other considerations.

Multipurpose reservoirs

With the increasing level of development of water resources throughout the world, it is becoming more and more important to plan projects which can serve a number of purposes simultaneously. For example, a planned storage reservoir may provide both water supply and flood control downstream. Hydrological data required for the design of a multipurpose project are basically an aggregate of the data required for the various single purposes involved. The methods of analysis, although similar to those applied in design of single-purpose reservoirs, are more complex. A series of plans involving combinations of project sizes and methods of operation are made to determine the optimum plan.

There is a basic conflict between the management of water resources for flood control and conservation (water supply and low-flow regulation) needs in multipurpose projects. During the flood season, it is usually essential to maintain empty space in reservoirs in anticipation of possible flood flows, whereas it is usually desired to keep the reservoir full for low-flow regulation. Toward the end of each flood season, this conflict is particularly critical because subsequent conservation benefits will depend partly on storage at that time, and it is, therefore, of particular importance to examine the project operation plans in relation to flood and low-flow expectation.

Water resources systems

If more than one water reservoir exists within a river basin or if water is diverted between basins where water resources projects exist, their overall effectiveness can be increased by coordinating the operation of each project. Such a coordination requires all the various projects to be treated as one interrelated system, considering the availability of water and the specific purposes of each project, as well as the possible interactions and trade-offs between them. A review of system operation should be undertaken as soon as a new project or a new demand is initiated that could have significant impact on existing operations.

Preliminary investigation of water management projects

Before appreciable expenditure of time and money can be justified for the role of dams and reservoirs of a water management project, a preliminary investigation is made of its feasibility, desirability, possible scope, and its possible effect on those hydrological factors which influence the environment and the efficiency of other projects, both existing and proposed. Although this investigation is based on whatever material may be available, such as fragmentary hydrological records, old maps, and reports, usually with only limited possibilities of supplementing it with new information through field surveys, aerial photographs, etc., it is carried out with great care since it is at this stage that conceptual planning decisions are often made and important aspects and consequences of the project may become apparent. If preliminary investigation indicates that the project potentialities are favorable, more detailed studies would normally be initiated.

Estimation of water demands

Estimates of water requirements for preliminary planning purposes may sometimes be made on the basis of the experience at similar existing projects in the same general area. However, estimates for final planning made on the basis of detailed studies of the present and possible future requirements for each purpose the reservoir is to serve are managed accordingly. Demands existing prior to the construction of a reservoir should be considered in the hydrological design of the project. Failure to consider these demands may cause economic losses and social

as well as legal problems in the operation and role of a reservoir. Navigation demands are usually for regulation of flow to maintain the minimum required water depth and the velocity below a safe maximum and for water volumes needed for passage through reservoir locks. In some cases, navigation depth requirements have to be met partially or entirely by dredging.

Municipal water supply

Water supply for municipalities is closely interrelated with problems of water quality. Quantitative municipal demand has usually little variation from season to season. However, a unique feature of this demand is the extremely high degree of dependability required owing to the potentially catastrophic consequences of shortages (epidemics, social disruption, etc.).

As with the municipal demand, the industrial demand is fairly constant throughout the year, and high-quality water is required in many cases.

Pollution abatement

Water quality in many rivers and reservoirs is less than desirable due to high concentration of pollutants. The situation is usually aggravated during dry periods when the ratio of effluent discharges to streamflow increases. Therefore, pollution abatement often requires low-flow augmentation to prevent the pollutants from exceeding a preset maximum level of concentration. Occasional flushing out of pollutants by surges of high flows from reservoirs is often desirable.

Nature of losses from reservoirs

Water losses, such as evaporation and seepage, occur under natural or preproject conditions and are reflected in the streamflow records used for estimating water supplies. The construction of new reservoirs and canals is often accompanied by additional evaporation and infiltration. Estimation of these losses may be based upon measurements at existing reservoirs and canals. The measured inflows, outflows, and rate of change of storage are balanced by the computed total loss rate.

In terms of water balance, seepage and infiltration do not constitute "loss" since they contribute to groundwater recharge or to discharge downstream from a structure, such as a dam, weir, navigation lock, etc. However, they constitute a "loss" as far as the primary purpose of the reservoir project is concerned, e.g., the water lost through seepage is lost for power generation or for withdrawal for water supply, etc. Thus, the term "loss" is to be understood in the water management, rather than hydrological, sense.

The depth of water evaporated annually from a reservoir surface may vary from about 400 mm in cool humid climates to more than 2,500 mm in hot arid regions. Evaporation is, therefore, an important consideration in many projects and deserves careful attention since it constitutes another demand on the circulable supply in storage.

Seepage loss from reservoirs, irrigation, and navigation canals may be appreciable if they are located in an area underlain by permeable strata. Curtailment of seepage losses can be expensive, and the technical difficulties involved can be such as to render a reservoir unfeasible.

Losses from irrigated areas

Water losses in an irrigation reservoir system may be several times greater than the water depth actually utilized by the crops. These losses are made up of excess water drained from the land surface or percolating to the groundwater, evaporation from the soil, transpiration of undesirable vegetation and seepage, and evaporation from canals. From 20% to 60% of the water diverted for irrigation may appear as return flow and contribute either to streamflow or to groundwater recharge. Chemical constituents in irrigation return flows are usually more concentrated than those in the original waters supplied and may contain new undesirable elements.

Evaporation from reservoirs

Prior to its submission by a reservoir, land loses water by evapotranspiration. For reservoir design purposes, the requirement is to estimate increased water loss from the reservoir area due to formation of a lake, that is, the difference between estimated reservoir evaporation and estimated preproject evapotranspiration from the land area. Direct measurement of evapotranspiration presents a number of still largely unsolved problems.

Multipurpose reservoirs

Most storage reservoirs serve a number of purposes, and it is usually not practicable to allocate a fixed portion of storage for each purpose. In most cases, such an allocation is restricted to emergency purposes. For example, a buffer zone is often created immediately above the dead storage zone and reserved for use in exceptional circumstances, such as flushing the downstream river section in case of some accidental contamination, emergency water supply in case of sudden health hazards, fire reserve, etc. Similarly, reservoirs may have an ungated emergency flood-control storage to prevent overtopping of the dam. However, most purposes are served from the same storage, and their requirements are accommodated by rather complex release rules for reservoir operation. Reservoir releases are often formulated in terms of rule curves indicating the rate of release as a function of the instantaneous storage and the time of the year.

The design and operation of multipurpose reservoirs requires complex analysis which is usually carried out by iterative methods involving adjustments of the rule curves and evaluation of the effects on all individual purposes, with the aim of optimizing the whole water management system involved. In such cases, the classical storage-draft-reliability relationships can only serve as the first approximation of the operating policy which is then gradually refined.

Systems of reservoirs

Procedures used in reservoir system design are similar to those described above for multipurpose projects. Because of the complex interactions among system components and between supplies and demands at various times and various locations, a direct solution is usually not feasible. Consequently, an initial design is first selected by engineering judgment and then improved by successive sequential routings.

A number of reservoirs in a basin are usually not designed as a system from the start, but the initial reservoir projects are often designed for specific purposes. As the resources of a river basin become increasingly utilized, it is necessary to study the operation of all projects as a system and to add new projects to the system from time to time. When this is done, operation of existing components might be changed, but major changes are usually difficult because of many legal, political, economic, and physical constraints. Accordingly, the level of optimization which can be reached in practice is usually rather low.

Selection of design floods

The general rule for the selection of the magnitude of the design flood is to reduce the risk of flooding (increase the design flood) inversely proportional to the extent of possible material damage. For structures involving low damage risk (such as culverts, secondary roads), the design flood may be calculated by empirical methods since the knowledge of its exact period is of relatively low importance. For structures or projects involving large potential damage but without the danger of the loss of life, design floods should be computed, wherever possible, by methods allowing an evaluation of their return periods in order that optimization methods could be used for selection of the design flood magnitude. For situations involving danger of loss of human life, the aim is to provide maximum protection and the maximum probable flood, or the standard reservoir flood is usually adopted as the design flood.

Design life of a reservoir

In the wide range of cases in which the design floods of a flood-control reservoir are selected by optimizing the relation between the expected flood damage and the cost of flood protection measures, the resulting optimum level of the calculated risk depends on the length of the period over which the performance of the reservoir is evaluated. This period is called the design life or planning horizon of the reservoir and is determined in the project planning stage on the basis of the following four time spans:

- (a) The physical life which ends when a reservoir or facility can no longer physically perform its intended function.
- (b) The economic life which ends when the incremental benefits from continued use no longer exceed the incremental cost of continued operation.

- (c) The period of analysis which is the length of time over which a reservoir may be expected to function under conditions that can be relatively accurately foreseen at the time of the analysis (operation in a distant future which is subject to a high degree of uncertainty is thus excluded from consideration).
- (d) The construction horizon which is reached when a facility is no longer expected to satisfy the future demands (functional obsolescence).

The optimum level of calculated risk and hence the design return period for each of these periods may be different, and the final selection of the design flood cannot be made without a consideration of political, social, environmental, and other nonquantifiable criteria.

Design floods for large reservoirs

The selection of design floods for spillway design for large storage reservoirs must be given special attention because of the fact that the reservoir may considerably change the flood régime both at the reservoir site and in the downstream section of the river.

Hydropower is solar energy in naturally and ideally concentrated form that can be utilized with the help of a mature and familiar technology with unsurpassed rates of efficiency and without depriving future generations in any way of raw materials or burdening them with pollutants or wastes. In many developing countries, it is the only natural energy resource. With a total annual generation of 2.1 million GWh, hydropower accounts today for 20% of electricity production and about 7% of total energy production worldwide. Even at a conservative estimate, the total exploitable hydropotential in the world amounts to at least six times as much. Very often, hydropower pays for multipurpose benefits, too. When this is taken into account, and when all environmental and social costs are internalized, hydropower compares favorably with other sources of energy.

Given the foreseeable depletion of fossil fuels, which presently are used to satisfy three quarters of primary energy requirements worldwide, plus the problem of the greenhouse effect and global warming, there is an urgent need to gradually replace them with methods of energy production which do not release CO₂, (or airborne mercury from coal-fired plants) into the atmosphere and which draw on renewable sources of energy. In the short and medium term, however, the predominant sources of renewable energy that will permit large-scale exploitation will be biomass and hydropower before new sources like the direct harnessing of the sun's energy by photovoltaics will be ready to make contributions of the same order of magnitude.

Power is generated at a rate which depends directly on the product of the discharge and a differential head of water. Hence, water demand depends on the required power output and the available head. Power plants attached to large reservoirs can use the available supplies more efficiently than run-of-river plants since they can store surplus water in the reservoir which cannot only

conserve water not needed immediately but also creates the head and thus reduces the discharges required. Run-of-river power plants can utilize only the discharge available at any specific time up to full turbine activity.

Control of floods

Flood control

Flood control is not a water use but generally a demand for a more uniform time distribution of streamflow. This can be partly achieved by various land-use management practices, such as afforestation of the basin, contour plowing, etc., but one of the most common means is the reduction of flood peaks by storing the excess water in reservoirs. There is a basic conflict between the objectives of flood control and of water conservation which has to be managed during operation of the reservoir.

Flood-control reservoirs

The volume of storage which must be provided in a reservoir will depend on the degree of flood abatement required and the flood characteristics of the stream. If flooding occurs only during certain periods of the year, the reservoir level may be drawn down before the danger of flooding begins and refilled as soon as the danger has passed. In such cases, flood abatement is achieved largely through reservoir operation schedules rather than by providing additional storage. However, in areas where a flash flood may occur almost any time during the year, storage capacity must be held in reserve at all times for temporary storage of flood waters.

Storage capacity to be held in reserve exclusively for flood control purposes can be provided either in on-stream or in off-stream reservoirs, while multipurpose storage is usually provided in on-stream reservoirs (An on-stream reservoir is a reservoir behind a dam constructed across a river, whereas an off-stream reservoir is situated aside from a river and is connected with it by canals, sills, or otherwise).

Regional detention storage

Full control over the flood-detention storage of a reservoir provides for the highest efficiency of the flood mitigation effect of this storage because it makes it possible to start storing water only after the highest permissible flow (also called the nondamaging flow) has been reached downstream from the reservoir. Only that portion of flood water which is apt to cause damage is stored.

The control over storage is achieved by regulation of a gated outlet in the case of an on-stream reservoir and of gated intake and outlet in the case of an off-stream reservoir. In an on-stream reservoir, full control is achieved only: (a) if the outlet has a capacity sufficient to release the nondamaging flow when the reservoir storage is at its minimum and (b) if the release of water from the detention storage can be fully regulated.

In an off-stream reservoir, full control is achieved only: (a) if the intake has a capacity sufficient to prevent the rise of flow in the downstream section of the river above the

nondamaging flow and (b) if the release of the detained water can be regulated.

It may also be mentioned that the design flood for the selection of the flood-detention storage capacity of a reservoir need not be the same as the design flood used for the design of its spillway since the safety requirements for the dam itself are usually different from the normal flood protection requirements downstream from the reservoir.

Unregulated on-stream detention storage

The storage above a fixed spillway crest of an on-stream reservoir is generally regarded as unregulated for design purposes, although it may be partially regulated by release through gated bottom outlets and turbines. However, for the design of the unregulated detention storage, either these releases are considered constant (often only a fraction of the actual outlet capacity) during the passage of a flood, or the outlets are considered closed. The former condition is usually adopted for the assessment of the normal downstream flood-control effects of the reservoir, while the latter condition is applied for the assessment of the dam safety.

The unregulated detention storage plays an important role in the safety of a dam against overtopping. Its design is interlinked with the design of the dam spillway and must be based on the same design flood as the spillway itself. Safety considerations in spillway design require that the reservoir be regarded as filled up to the spillway crest at the beginning of the design flood.

Unregulated off-stream detention storage

This type of storage arises in off-stream reservoirs (sometimes called "polders" because of structural resemblance to real polders) constructed by enclosing a part of a flood plain by a dyke whose crest at the upstream end is lowered to form a sill, i.e., an intake into the enclosure. When the river stage at the upstream end rises above the sill crest, the polder starts filling by overflow over the sill, thereby reducing the flow in the river. The fact that the river bypasses the reservoir makes the unregulated off-stream storage more efficient than unregulated on-stream storage since the unnecessary filling starts later.

Operation considerations for design purposes

Flood-detention storage is most frequently provided in multipurpose on-stream reservoirs with gated outlets of a capacity sufficient to provide a high degree of control of the reservoir storage. These reservoirs always have some ungated flood-detention storage (either because the spillway has no gates or, if it has, some storage above the crest of the gates must be provided to allow an emergency overflow of the gates which may become stuck in the closed position) and, in many cases, they also have a designated part of the gated storage reserved for flood detention. In addition, storage designated for other uses may occasionally be used for flood control purposes.

This diversity offers great flexibility and makes the flood reduction strongly dependent on the mode of reservoir operation. It is, therefore, necessary in such cases to analyze many different operation modes during the early stages of design since the results may affect the selection of the design variables for the project.

Time interval between successive floods

The use of storage reservoirs to reduce floods raises the question of a possible occurrence of two or more floods in close succession and hence the possibility that the detention storage filled by one flood may not be emptied before the arrival of the next flood. The problem is essentially one of frequency distribution of the times between flood events (volumes, peaks) of specified magnitudes and can be solved by frequency analysis of historical streamflow records, synoptic weather patterns, or synthetic streamflow records derived from precipitation records via deterministic models. However, care must be taken in extrapolating the frequency curves of the between-flood intervals in order to prevent the violation of physical constraints. Thus, for instance, where major floods are caused by snowmelt then, once the snow has melted and the corresponding flood has passed, the time to the next flood must be longer than the whole period of above-freezing temperatures. If this period is a number of months, it would be meaningless to extrapolate the frequency curve down to time intervals of a few weeks or days. Similarly, even if frequent curves derived from historical records for two areas – one of which was subject to tropical cyclones and the other, not – were identical, the likelihood of two major storms occurring only a few days apart would be much higher in the cyclone-affected area than in the other one.

Flood control has always been a particularly significant motive for dam construction and frequently its primary purpose. It will continue to be so as long as about 40% of all fatalities from natural catastrophes worldwide are caused by flooding, amounting to a frightening total of nearly 100,000 per year. Compared with the main requirements of irrigation, domestic and industrial water supply, energy production, and flood control, the other purposes and benefits of dams, such as navigation, fisheries and tourism, improvements to the infrastructure, job creation, and on-site training, are of generally minor importance but must nevertheless not be disregarded or underrated.

In spite of this, there has been hint of a change in the United States, and an environmental lobby has existed there since the 1980s, who are generally opposed to further dam building in the USA; “much of our water has been developed; we have developed thousands of huge lakes, some more than a hundred miles long, flooding an area the size of Vermont and New Hampshire combined; we have made more than two and a half million smaller lakes and ponds. We have turned dangerous rivers into staircases for ships and transformed the ancient roar of rapids into the hum of electricity; the flow of deep,

cold water from the bottom of reservoirs is often so poor in oxygen that all aquatic life downstream is affected.” (*National Geographic*)

‘Flow gently sweet Afton among thy green braes
‘We’ll be damming thee up in a couple o’ days’

Clearly, a difficult problem on water resources management may arise in such circumstances, which has to be resolved.

Future upstream development effects

The design of a flood-control reservoir is based upon analyses of floods which occurred in the past, although the reservoir is to control future floods. The growth of population and the increase in the standard of living result in an intensified land development. Forests are transformed into agricultural lands, drainage of agricultural lands is improved, etc. The change from manual labor to mechanization in agriculture, the extension and intensification of urbanization, etc., often contribute to increased volumes and discharges of surface runoff and, frequently, also of sediment transport. On the other hand, application of sound soil conservation practices contributes to their decrease. Evaluation of the hydrological effects of land development is difficult, yet the hydrologist should be aware of its effects of increasing flood risk.

Estimation of maximum reservoir levels

Reservoirs are designed for water levels somewhat higher than those which may be attained during the maximum flood as a safety measure against wind setup, wave action, wave run-up, and periodic undulations of the water surfaces (seiches). This “freeboard,” or allowance for additional rises in water level, cannot be considered as adding to the useable storage, although it may provide a factor of safety against floods greater than the maximum design flood. Greater freeboard is usually provided for earth dams, particularly in areas subject to earthquake effects or severe frost action.

Wind setup

The result of wind blowing over the water surface of a reservoir is to pile up water at the leeward end of the reservoir and to lower the water level at the windward end. This wind setup and setdown is more pronounced in shallow than in deep water.

Winds blowing across reservoirs also generate waves that eventually reach and run up on lake shores and the upstream face of dams. Adequate freeboard to prevent overtopping of a dam by waves is required. The run-up of the waves is a function of the wave height, wave length, and the slope of the embankment.

Reservoir design must normally be based on wind data obtained at land stations with an overland fetch to the recording site. One of the most difficult meteorological problems in estimate wave heights is determining the wind field over the lake from land-based wind observations.

The ratio of wind speed over land to wind speed over the lake depends on the stability of the air mass over the lake, which depends on the temperature difference between the water surface and the overlying air. It also depends on the "roughness" of the topography at the land-based measuring station.

Waves are critical only when a reservoir is near full storage level. Thus, only winds which can occur during the season(s) of high water levels need to be considered. The height above the still water level to which the water will rise as a result of wave action is termed "the run-up." This elevation depends on the embankment slope and wave steepness.

Periodic undulations of water surface

In restricted bodies of water, such as reservoirs, periodic water surface undulations may be caused by variations in the rate of inflow or outflow, wind action, sudden changes in atmospheric pressure, or by earth temperature. Depending on the physiographical characteristics of the reservoir, these waves may be reflected either from shorelines or at places where abrupt changes occur in the reservoir width or depth. In a long, narrow body of water, a series of waves may be set up with several nodes and antinodes.

There is no method available for computing the height of waves due to such causes as a sudden change in atmospheric pressure or earth tremors. Total freeboard allowance for these phenomena may vary from several centimeters up to about 1 m, depending on the size and importance of the reservoir.

Sedimentation

When approaching its mouth, the flow velocity of a river decreases and with it, the ability to carry sediment (Coarse sediments aggrade first, interfere with the channel conveyance, and may cause additional river meanders and distributaries). The area of the flowing water expands, the depth decreases, the velocity is reduced, and eventually, even fine sediments begin to aggrade. As a result, deltas may be formed in the upper portion of reservoirs. The deposited material may later be taken to lower portions by hydraulic processes within the water body.

Sediments are deposited in accordance with their settling velocity. A relationship between the grain size and the settling velocity may be developed. A considerable concentration of suspended sediments may remain in the water for several days after their arrival into a reservoir, which may interfere with the use of the stored water for certain purposes, such as water supply or recreation.

It should be emphasized that not all of the sediment formed aggrades in a reservoir. A large portion of it remains in the upper zones of the watershed, some is deposited upstream from reservoirs, and some is carried downstream by the released water. The sediment trapping efficiency in a reservoir depends upon the hydraulic

properties of the reservoir, nature of the sediment, and the hydraulic properties of the outlet. The density of newly deposited sediments is relatively low but increases with the passage of time. The organic component in the sediment may undergo change which may reduce its volume and enhance biochemical processes in the stored water.

Sediment control measures fall into two broad categories: (a) land treatment measures for watershed protection and (b) structural measures. The aim of land treatment measures is to reduce erosion in the watershed and thereby the rate of sediment formation by improving the protective cover on the soil surface, reducing surface runoff, and increasing infiltration rates.

The deposition of sediments reduces the storage capacity of a reservoir and thereby the reservoir's ability to perform its function. Most reservoirs have a certain part of their storage capacity designated for sediment deposition in order to prevent the reduction of the active storage. However, it often happens that this storage is inadequate. The flood-detention storage is usually significantly affected since it occupies the upstream part of the reservoir where sedimentation often occurs due to both bank erosion (along the whole circumference) and river-sediment deposition (upstream part of reservoir). Thus, it is generally the case that the flood-reduction efficiency of a reservoir decreases with time. This should be considered in long-term flood protection planning in order that alternative measures can be developed in time.

Thermal stratification

Thermal stratification is a result of natural factors. However, thermal pollution may be a contributing element. Thermal stratification corresponds, particularly in nutrient-rich lakes, to dissolved oxygen stratification and frequently to the stratification of other dissolved substances.

The epilimnion, i.e., the upper layer of water which is warmer in summer, generally has higher water quality. In the upper layer, one may expect reduction in silicate content following an increase in diatoms and decreased hardness due to inflow of direct precipitation water that did not have prior contact with the soil or an opportunity for biogenic extraction of calcium.

The hypolimnion, i.e., the deeper layer of water which is colder in summer, has a reduced dissolved oxygen concentration. One may expect an accumulation of various substances in this layer due to deposition on the bottom and absorption by sediment and in living organisms. Anaerobic decomposition of algae and other organisms usually occurs in the hypolimnion. One may expect the hypolimnion to show trends of increasing concentration of ammonia and hydrogen sulfide, reduction in nitrate and sulfate concentration, accumulation of sediment and occasionally of heavy metals, and periodic increases in iron, manganese, and phosphate concentration. During the turnover, caused by the seasonal cooling

of the surface layer of the lake, a convective circulation takes place, which results in mixing and a uniform temperature.

In addition to the effects listed above, one may expect that in large lakes and reservoirs, organic matter is biodegraded to a large extent due to long residence time, that variations in water quality are dampened out for the same reason, and that algae trigger the formation of chelating substances and halocarbons (Figure 1).

Effects of reservoirs on water quality in streams and rivers

By raising the water level, a dam – and to a lesser extent, a weir – has usually the following effects on water quality in the upstream reach of the river:

- Intensification of self-purification processes due to increased residence time in the reach, better sedimentation of suspended solids resulting in increased solar radiation, and in changes in the sediment characteristics of the river bed.
- This in turn leads to a rise in phytoplankton production, greater oxygen consumption, and increased day–night fluctuations in oxygen, pH value, and CO₂.

Fish migration is usually disturbed both by the physical barrier and by changes in water quality. Changes in bank vegetation, which are governed by local topography, climate, and water level variation, may also affect water quality. In cold climates, dams – and to a lesser extent, weirs – create favorable conditions for an extended duration of the ice cover in the upstream reach. This leads to a decreased reaeration. Further effects in the case of large storage volumes may result from thermal

stratification. Increased pollution loads retained in the upstream reach may lead to eutrophication or to anaerobic conditions.

The effects of a dam or weir on water quality in the downstream reach depend on the upstream storage volume, dam design and operation, and other factors. The most important effects are the following:

- Reduction in suspended solid load pollution load and turbidity.
- Changes in the chemical characteristics of the water, often a lower concentration of dissolved oxygen and nitrates, and increases in phosphate, CO₂ and H₂S, the latter particularly when anaerobic conditions prevail upstream.
- Decrease in the summer water temperature and increase in the winter temperature.
- Reduction of the day–night temperature fluctuation to which the river flora and fauna are adapted.

Flow reduction and augmentation

In addition to the flow-regulation effects of dams, many water resource projects involve flow reduction by abstractions for various water supply purposes or augmentation due to inputs of water coming from sources outside the basin.

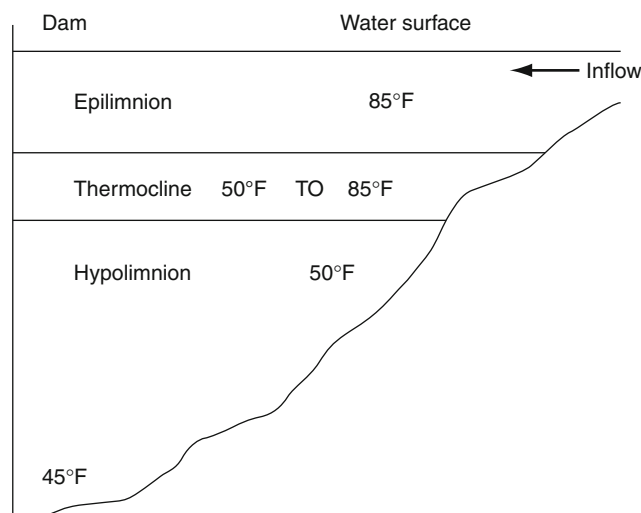
When the abstracted water undergoes a treatment and the resulting sludge and residues are dumped in the donor river, or when the abstracted water is obtained from the less polluted turbid portions of the river cross-section, the abstraction effects are equivalent to a reduction in flow and to a pollution input. The disposal of sludge and residues is usually subject to control by legal requirements for the quality of effluents.

The effects of flow augmentation depend mainly on the quality of the additional water as compared to that of the river water. An addition of water of poorer quality is equivalent to a pollution input.

Water quality in large lakes and reservoirs

Water quality in large lakes and reservoirs can be improved or worsened by water resource projects, depending upon the nature and operation régime of the project. A water resource project involving a withdrawal of water of a better-than-average quality (e.g., from the epilimnion) will generally worsen the water quality in the lake. The same is true when water of a poorer-than-average quality is introduced into the lake or reservoir.

Water quality in a large reservoir depends to a large extent upon the characteristics of the underlying terrain before flooding and upon the treatment applied to it. If the future reservoir bottom is covered by soils with rich organic (humus) content, the latter is leached after the reservoir is filled, and accelerated eutrophication may result. This may be avoided by removal of vegetation and soil prior to flooding which usually is a costly operation.



Dams and Reservoirs, Role, Figure 1 Representative profile showing summer stratification in a large storage reservoir, with a high dam (World Meteorological Organization, 1983).

Water quality changes due to pollution relate to physical, chemical, and biological characteristics of the body of water. The effects of pollution on lakes are generally different from those on rivers because of the differences in the hydraulic, hydrological, and ecological conditions. In addition, lakes are liable to present a significant variation in water quality, whereas rivers are generally more homogeneous, although significant quality variation may sometimes occur in rivers downstream of significant inflow points.

Eutrophication

One of the most common forms of pollution is related to excessive concentrations of nutrients originating either in urban waste waters or in rural runoff. This usually results in excessive development of algae populations – particularly in areas with low water velocity – and in significant reduction or disappearance of a number of plant and animal species. This process is known as eutrophication.

Eutrophication is, in fact, a natural process marking the maturing and aging of lakes. However, under conditions not involving man's activity, this process takes hundreds or thousands of years, depending upon lake size, hydrological conditions, and land cover in the basin. Civilization, particularly in its current industrialized form, is responsible for accelerated eutrophication in a large number of lakes all over the world.

The problem of eutrophication and its causative factors is one of the current major water quality problems. Although much research has been devoted to it, it is not yet possible to explain quantitatively the process of nutrient enrichment composition of certain industrial products (e.g., elimination of phosphorus compounds from detergents), artificial cooling of industrial wastewaters, etc.

If pollution originates in the matter washed away by runoff from the surface of a river basin (e.g., pesticides and herbicides, fertilizers, urban uncontrolled waste), pollution abatement can be obtained only by changing the practices that lead to uncontrolled spreading of the pollutants in the river catchment and measures to reduce runoff and soil erosion.

Significant pollution is generated by soil erosion. Prevention in this field requires adequate forestry management and construction and farming practices. Finally, pollution from leachate resulting from garbage dumps is locally very significant. By appropriate location and design of such dumps, this can be avoided.

Corrective measures

Reducing pollution in water bodies after pollutants have reached them is generally difficult and costly. In most cases, it is possible only to treat the water abstracted from the water body for various purposes (e.g., domestic or industrial water supply). However, in special circumstances, some remedial work can be done for the whole water body. Such remedial work consists, in the case of rivers, mainly in artificial

reaeration (oxygenation), or mixing and dredging of settled pollutants, and, in the case of lakes and reservoirs, of the following measures:

- Emptying the lake regularly during the period between late fall and early spring to expose the organic matter directly to air and permit the aerobic decomposition of organic matter.
- Dredging the bottom of the lake in the areas which contain most of the organic and polluting matter.
- Forced reaeration by compressed air in the deoxygenated layers and “harvesting” and disposing of organic matter produced in the form of algal bloom, undesirable fish, etc.

The first two measures have a negative side effect, the killing of fish. Remarkable work in the last three measures has been carried out in Sweden.

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Cross-references

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[Dams, Flood Protection, and Risk](#)
[Large Dams and Environment](#)
[Large Dams, Statistics and Critical Review](#)

DAMS, CLASSIFICATION

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Introduction

Demand for water is increasing worldwide at twice the population growth which itself is growing at the rate of 90 million a year.

Annual precipitation is estimated at some 110,000 km³, of which 70,000 km³ evaporates or infiltrates. Of the remainder, 40,000 km³ runs into the oceans, 14,000 km³ into rivers, and 26,000 km³ below ground as groundwater.

Seasonal variations of both rainfall and runoff can be significant, and freshwater resources are unevenly distributed and in some cases deserts which rarely see rain and humid areas where floods occur practically every year.

It is clear, therefore, that storage is required to satisfy demand even in regions with abundant rainfall. If not,

the runoff of whole regions may be lost to the oceans and regional demand may not be met.

The present world storage capacity is about 6,000 km³. It follows that in order to satisfy worldwide demand, the necessary increase in storage may only be met by dams.

Purposes of dams generally include:

- Irrigation 48% of all dams
- Hydroelectric power 20% worldwide: in Europe 40%
- Water supply 15%
- Flood control 8%
- Recreation 4%
- Inland navigation and fish farming

Dam construction

Types of dam construction are:

- Earth 64%
- Gravity 19%
- Rockfill 8%

Dams, Classification, Table 1 Number of dams by country members

N ⁰	All dams registered Country/Pays	Nb	N ⁰	Dams with H>= 30 m Country/Pays	Nb	N ⁰	Dams with H>= 60 m Country/Pays	Nb
1	USA	9,265	1	China	4,685	1	China	434
2	China	4,688	2	USA	1,533	2	Japan	365
3	India	4,636	3	Japan	1,075	3	USA	355
4	Spain	1,267	4	Spain	517	4	Spain	187
5	Korea (ROK)	1,205	5	India	504	5	Turkey	115
6	Japan	1,121	6	Turkey	376	6	Italy	111
7	South Africa	915	7	Italy	322	7	India	91
8	Canada	793	8	Brazil	245	8	Brazil	69
9	Brazil	635	9	Mexico	202	9	Iran	66
10	Turkey	625	10	Australia	201	10	France	60
11	France	597	11	France	198	11	Mexico	53
12	Italy	549	12	Canada	177	12	Australia	51
13	Mexico	536	13	South Africa	170	13	Switzerland	48
14	United Kingdom	517	14	Korea (ROK)	158	14	Canada	46
15	Australia	507	15	Norway	115	15	Romania	31
16	Norway	335	16	United Kingdom	114	16	Germany	25
17	Albania	306	17	Germany	98	17	Morocco	25
18	Germany	306	18	Iran	91	18	Norway	25
19	Zimbabwe	253	19	Switzerland	88	19	Korea (ROK)	24
20	Romania	246	20	Romania	85	20	Portugal	24
21	Thailand	218	21	Albania	83	21	Algeria	22
22	Sweden	190	22	Austria	82	22	Argentina	22
23	Bulgaria	180	23	Argentina	73	23	Colombia	20
24	Austria	168	24	Portugal	72	24	Greece	19
25	Switzerland	159	25	Bulgaria	64	25	Russia	19
26	Portugal	151	26	Russia	60	26	South Africa	18
27	Iran	135	27	Morocco	53	27	Austria	17
28	Czech Rep	118	28	Zimbabwe	52	28	Chile	17
29	Algeria	114	29	Venezuela	49	29	Venezuela	17
30	Argentina	108	30	Algeria	48	30	Bulgaria	15
31	Morocco	104	31	Indonesia	48	31	Indonesia	15
32	Indonesia	100	32	Thailand	46	32	Yugoslavia	14
33	Tunisia	100	33	Czech Rep	43	33	New Zealand	12
34	New Zealand	96	34	New Zealand	43	34	F.Y.R.O. Macedonia	10

Dams, Classification, Table 1 (Continued)

N ⁰	All dams registered Country/ <i>Pays</i>	Nb	N ⁰	Dams with H ≥ 30 m Country/ <i>Pays</i>	Nb	N ⁰	Dams with H ≥ 60 m Country/ <i>Pays</i>	Nb
35	Russia	91	35	Sweden	42	35	Malaysia	10
36	Chile	87	36	Yugoslavia	42	38	United Kingdom	10
37	Venezuela	76	37	Greece	41	37	Thailand	9
38	Pakistan	71	38	Colombia	40	38	Bosnia-Herzegovina	7
39	Poland	69	39	Chile	36	39	Czech Rep	7
40	Yugoslavia	69	40	Malaysia	33	40	Pakistan	7
41	Greece	60	41	Cyprus	25	41	Sweden	7
42	Malaysia	60	42	Tunisia	22	42	Albania	6
43	Colombia	58	43	Syria	20	43	Dominican Rep	6
44	Finland	56	44	F.Y.R.O. Macedonia	16	44	Peru	6
45	Peru	56	45	Pakistan	18	45	Zimbabwe	6
46	Cyprus	52	46	Poland	18	46	Tunisia	5
47	Slovakia	50	47	Bosnia-Herzegovina	16	47	Belgium	3
48	Sri Lanka	46	48	Slovakia	16	48	Cyprus	3
49	Nigeria	45	49	Peru	15	49	Honduras	3
50	Syria	41	50	Slovenia	14	50	Iraq	3
51	Slovenia	30	51	Dominican Rep	11	51	Poland	3
52	Croatia	29	52	Sri Lanka	11	52	Slovakia	3
53	Bosnia-Herzegovina	25	53	Libya	10	53	Sri Lanka	3
54	Ivory Coast	22	54	Belgium	9	54	Syria	3
55	Iceland	20	55	Croatia	9	55	Congo (DRC)	2
56	F.Y.R.O. Macedonia	18	56	Iceland	8	56	Costa Rica	2
57	Ireland	16	57	Nigeria	8	57	Croatia	2
58	Belgium	15	58	Finland	7	58	Lesotho	2
59	Hungary	15	59	Congo (DRC)	6	59	Libya	2
60	Congo (DRC)	14	60	Iraq	5	60	Nigeria	2
61	Libya	12	61	Ivory Coast	5	61	Uruguay	2
62	Dominican Rep	11	62	Uruguay	5	62	Zambia	2
63	Netherlands	11	63	Bolivia	4	63	Egypt	1
64	Denmark	10	64	Burkina Faso	4	64	Ghana	1
65	Madagascar	10	65	Cameroon	4	65	Guatemala	1
66	Cameroon	9	66	Honduras	4	66	Lebanon	1
67	Costa Rica	9	67	Ireland	4	67	Nepal	1
68	Iraq	9	68	Lesotho	4	68	Paraguay	1
69	Lesotho	9	69	Paraguay	4	69	Slovenia	1
70	Burkina Faso	8	70	Zambia	4	70	Sudan	1
71	Honduras	8	71	Costa Rica	3	71	Bolivia	0
72	Bolivia	6	72	Luxemburg	3	72	Burkina Faso	0
73	Egypt	6	73	Sudan	3	73	Cameroon	0
74	Uruguay	6	74	Egypt	2	74	Denmark	0
75	Ghana	5	75	Ghana	2	75	Finland	0
75	Lebanon	5	76	Guatemala	2	76	Hungary	0
77	Guatemala	4	77	Lebanon	2	77	Iceland	0
78	Paraguay	4	78	Netherlands	2	78	Ireland	0
79	Sudan	4	79	Nepal	1	79	Ivory Coast	0
80	Zambia	4	80	Denmark	0	80	Luxemburg	0
81	Luxemburg	3	81	Hungary	0	81	Madagascar	0
82	Nepal	3	82	Madagascar	0	82	Netherlands	0

- Arch 4%
- Buttress 1.4%
- Barrage 0.8%
- Multiple arch 0.5%

Generally, dams less than 30 m high represent about 62% of all dams, dams less than 59 m account for 90% of the total, and only 2% are more than 100 m high.

Records of the world's dams are kept by the International Commission on Large Dams (ICOLD) in Paris. In 1950, there were only 5,196 dams in service in the world. Today there are of the order of some 36,000.

The given tables classify the number of dams by country (Table 1), the highest dams of the world (Table 2), and the dams with height over 150 m (Table 3).

Dams, Classification, Table 2 World's highest dams

N ^o	Dam name/ <i>Nom du barrage</i>	Height/ <i>Hauteur</i>	Purposes/ <i>Buts</i>	Country/ <i>Pays</i>	Continent/ <i>Continent</i>
1	Rogun	335	H,I	Tajikistan	Asia
2	Nurek	300	I,H	Tajikistan	Asia
3	Xiaowan (yunnan)	292	HCIN	China	Asia
4	Grande Dixence	285	H	Switzerland	Europe
5	Inguri	272	H,I	Georgia	Europe
6	Vajont	262	H	Italy	Europe
7	Manuel m. torres	261	H	Mexico	America N.
8	Tehri	261	IS	India	Asia
9	Alvaro obregon	260	IS	Mexico	America N.
10	Mauvoisin	250	H	Switzerland	Europe
11	Alberto lleras c.	243	H	Colombia	America S.
12	Mica	243	H	Canada	America N.
13	Sayano –shushenskaya	242	NH	Russia	Asia
14	Ertan	240	H,C,I	China	Asia
15	La esmeralda (chivor)	237	H	Colombia	America S.
16	Kishau	236	IH	India	Asia
17	Oroville	235	CISHR	United States	America S.
18	El cajon	234	HICR	Honduras	America N.
19	Chirkey	233	H,I,S	Russia	Europe
20	Shuibuya	233	HCN	China	Asia
21	Bhakra dam	226	IH	India	Asia
22	Luzzzone	225	H	Switzerland	Europe
23	Hoover	223	SHI	United States	America N.
24	Karoun – 4 (monj)	222	H	I. Rep. Iran	Asia
25	Contra	220	H	Switzerland	Europe
26	Mratinje	220	H	Yugoslavia	Europe
27	Dworshak dam and res	219	CHRSF	United States	America N.
28	Glen canyon	216	HIRX	United States	America N.
29	Toktogul	215	H,I	Kirghizstan	Asia
30	Daniel johnson (manic 5)	214	H	Canada	America N.
31	Keban	210	H	Turkey	Europe
32	Zimapan	207	H	Mexico	America N.
33	Bakun dam	205		Malaysia	Asia
34	Irape	205	H	Brazil	America S.
35	Karoun-3	205	I,H	I.Rep. Iran	Asia
36	Lakhwar	204	IH	India	Asia
37	Dez	203	IH	I. Rep. Iran	Asia
38	Almendra	202	H	Spain	Europe
39	Berk	201	H	Turkey	Europe
40	Khudoni	201	H	Georgia	Europe
41	Koelnbrein	200	HI	Austria	Europe
42	Shahid abbas-pour	200	I,H	I. Rep. Iran	Asia
43	New bullards bar	197	HCISFR	United States	America N.
44	Campos novos	196	H	Brazil	America S.
45	Itaipu	196	HN	Brazil/Paraguay	America S.
46	Altinkaya	195	H	Turkey	Europe
47	Seven oaks dam	193	C	United States	America N.
48	Longtan (guangxi, tian'e)	192	CHI	China	Asia
49	New melones	191	ICHRF	United States	America N.
50	Miel i	188	H	Colombia	America S.
51	Aguamilpa	187	H	Mexico	America N.
52	Kurobe	186	H	Japan	Asia
53	Sanbanxi	186		China	Asia
54	Zillerguendl	186	H/C	Austria	Europe
55	Barra grande	185	H	Brazil	America S.
56	Gotvand,e olya	185	H	I. Rep. Iran	Asia
57	Katse	185	S	Lesotho	Africa
58	Oymapinar	185	H	Turkey	Europe
59	Mossyrock	185	HCR	United States	America N.
60	Shasta	183	INSHR	United States	America N.
61	Bennett w.a.c.	183	H	Canada	America N.
62	Deji	181	HIC	China	Asia

Dams, Classification, Table 2 (Continued)

N ^o	Dam name/ <i>Nom du barrage</i>	Height/ <i>Hauteur</i>	Purposes/ <i>Buts</i>	Country/ <i>Pays</i>	Continent/ <i>Continent</i>
63	Sanxia (three gorges)	181	CHNI	China	Asia
64	Amir-kabir	180	I,S,H	I. Rep. Iran	Asia
65	Dartmouth	180	IHS	Australia	Australasia
66	Emosson	180	H	Switzerland	Europe
67	Hongjiadu	180	HCS	China	Asia
67	Tignes	180	H	France	Europe
69	Hasan ugurlu	179	H	Turkey	Europe
70	Don pedro main	178	HICFR	United States	America N.
71	Longyangxia	178	HCSI	China	Asia
72	Simareh (hini mini)	178	H	I. Rep. Iran	Asia
73	Tianshengqiaoyiji	178	HIC	China	Asia
74	Masjeo soleyman	177	H	I. Rep. Iran	Asia
75	Takase	176	H	Japan	Asia
76	Revelstoke	175	H	Canada	America N.
77	Alpe gera	174	H	Italy	Europe
78	Karakaya	173	H	Turkey	Europe
79	Hungry horse	172	IHC	United States	America N.
80	Cahora bassa	171	I, H, C	Mocambique	Africa
81	Daniel palacios	170	H	Ecuador	America S.
82	Maroun	170	I,H	I. Rep. Iran	Asia
83	Piedra del aguila	170	HC	Argentina	America S.
84	Sykia	170	HI	Greece	Europe
85	Thissavros	170	H	Greece	Europe
86	Ataturk	169	IH	Turkey	Europe
87	Idukki	169	H	India	Asia
88	Charvak	168	H,I	Uzbekistan	Asia
89	Gura apelor	168	H	Romania	Europe
90	Lg deux principal cd-oo	168	H	Canada	America N.
91	Grand coulee	168	IC	United States	America N.
92	Fierze	167	H	Albania	Europe
93	Thomson	166	SI	Australia	Australasia
94	Vidraru	166	H	Romania	Europe
95	Wujiangdu	166	HC	China	Asia
96	Ross	165	H	United States	America N.
97	Trinity	164	IHCR	United States	America N.
98	Akkopru	163	IHC	Turkey	Europe
99	Candelaria	163	X	Chile	America S.
100	Dongfeng (Guizhou, qingzhen)	162	H,C	China	Asia
101	Guri	162	H	Venezuela	America S.
102	Talbingo	162	H	Australia	Australasia
103	Tokuyama	161	CHS	Japan	Asia
104	Yellowtail	160	ICHXRS	United States	America N.
105	Foz do areia	160	H	Brazil	America S.
106	Grandmaison	160	H	France	Europe
107	Kremasta	160	HF	Greece	Europe
108	Los leones – Final stage	160	X	Chile	America S.
109	Songwon	160	HI	Korea N (RDK)	Asia
110	Cougar	158	HCIRSX	United States	America N.
111	Canales	158	I	Spain	Europe
112	Emborcação	158	H	Brazil	America S.
113	Gokcekaya	158	HI	Turkey	Europe
114	Naramata	158	CHIS	Japan	Asia
115	Yacambu	158	S/C/R	Venezuela	America S.
116	Dongjiang	157	H,C,I,S	China	Asia
117	Okutadami	157	H	Japan	Asia
118	Sakuma	156	H	Japan	Asia
119	Zeuzier	156	H	Switzerland	Europe
120	Zlpingpu	156	CHIS	China	Asia
121	Göscheneralp	155	H	Switzerland	Europe
122	Kenyir	155	C,H,R	Malaysia	Asia
123	Lijiaxia	155	HCI	China	Asia
124	Miyagase	155	CHS	Japan	Asia

Dams, Classification, Table 2 (Continued)

N ^o	Dam name/ <i>Nom du barrage</i>	Height/ <i>Hauteur</i>	Purposes/ <i>Buts</i>	Country/ <i>Pays</i>	Continent/ <i>Continent</i>
125	Monteynard	155	H,R	France	Europe
126	Nagawado	155	H	Japan	Asia
127	Nukui	155	CHS	Japan	Asia
128	Place moulin	155	H	Italy	Europe
129	Ralco	155	H	Chile	America S.
130	Urayama	155	CHS	Japan	Asia
131	Bhumibol	154	IHCS	Thailand	Asia
132	Serra da mesa	154	H	Brazil	America S.
133	Tedorigawa	154	CHIS	Japan	Asia
134	Xiaolangdi	154	CSIH	China	Asia
135	Flaming gorge	153	SHRC	United States	America N.
136	Curnera	153	H	Switzerland	Europe
137	Gepatsch	153	H/C	Austria	Europe
138	Ostour	153	I,H	I. Rep. Iran	Asia
139	Huites	152	HI	Mexico	America N.
140	Jilintai	152	SIH	China	Asia
141	Santa giustina	152	H	Italy	Europe
142	Sazbon	152	H	I. Rep. Iran	Asia
143	Geheyang	151	H,C,N	China	Asia
144	Menzelet	151	IHC	Turkey	Europe
145	Zervreila	151	H	Switzerland	Europe
146	Carver lake dam	151	R	United States	America N.
147	Baishan	150	H,C,I,S	China	Asia
148	Canelles	150	H	Spain	Europe
149	Finstertal	150	H	Austria	Europe
150	Messochora	150	H	Greece	Europe
151	Roselend	150	H	France	Europe
152	Shafa rood	150	I,S,H	I. Rep. Iran	Asia
153	Turkwel	150	H	Kenya	Africa
154	Xingo	150	H	Brazil	America S.

Dams, Classification, Table 3 Dams with height over 150 m (38/40)

Name of dam	Year of completion	River	State or province	Type (see note 1)	Height (m)	Crest length (m)	Reservoir volume (10 ³ m ³)	Purpose (see note 2)
<i>Albania</i>								
Fierze	1978	Drin	Tropoje	ER	167	400	2,700,000	H
Koman	C	Drin	Shkoder	ER	133	275	450,000	H
<i>Australia</i>								
Talbingo	1971	Tumut	N.S.W.	ER	162	701	921,400	H
Dartmouth	1979	Mitta Mitta	Victoria	ER	180	670	4,000,000	H
Thomson	1984	Thomson	Victoria	ER	164	1,180	1,175,000	SI
<i>Austria</i>								
Gepatsch	1965	Faggenbach	Tyrol	ER	153	600	140,000	H
Kölnbrein	1977	Malta	Carinthia	VA	200	626	205,000	H
Finstertal	1980	Tr. Nederbach	Tyrol	ER	150	652	60,500	H
Zillergründl	1986	Ziller	Tyrol	VA	186	506	90,000	H
<i>Brazil</i>								
Foz Do Areia	1980	Igaçu	Paraná	ER	160	850	6,100,000	H
Emborcação	1982	Paranaíba	Minas Gerais/ Goiás	ER	158	1,607	17,600,000	H
Itaipu	1982	Paraná	Brazil/Paraguay	ER/PG/ TE	196	7,900	29,000,000	H
<i>Canada</i>								
W.A.C. Bennett	1967	Peace	British Columbia	TE	183	2,042	70,308,930	H

Dams, Classification, Table 3 (Continued)

Name of dam	Year of completion	River	State or province	Type (see note 1)	Height (m)	Crest length (m)	Reservoir volume (10 ³ m ³)	Purpose (see note 2)
Daniel Johnson (Manic 5)	1968	Manicouagan	Quebec	MV	214	1,314	141,851,350	H
Big Horn Abraham Lake Res.	1972	North Sask.	Alberta	TE	150	472	1,768,000	H
Manicouagan 3	1975	Manicouagan	Quebec	TE	108	366	10,422,991	H
Barrage principal	1978	La Grande Riviere	Quebec	ER	168	2,826	61,715,000	H
Barrage Nord	1981	La Grande	Quebec	ER	93	2,156	60,020,000	H
<i>China</i>								
Wujiangdu	1981	Wu Jiang	Guizhou	VA	165	368	2,300,000	H
Baishan	1990	Songhua Jiang	Jilin	VA	150	670	6,215,000	H
Longyangxia	1990	Huang He	Qinghai	VA	172	342	24,700,000	HIS
<i>Columbia</i>								
Chivor (La Esmerelda)	1975	Batá	Boyacá	ER	237	280	815,000	H
Salvajina	1985	Cauca	Cauca	ER	160	360	904,000	H
Guavio	1987	Guavio	Cundinamarca	ER	243	390	1,020,000	H
<i>Ecuador</i>								
Daniel Palacios (Amaluza Res.)	1983	Paute	Azuay	PG/VA	167	420	120,000	H
<i>France</i>								
Grand'Maison	1985	Eau d'Olle	Isère	TE/ER	160	550	140,000	H
<i>Greece</i>								
Kremasta	1965	Achelöos	Etolo-Akarnania	TE	165	460	4,750,000	H
<i>India</i>								
Bhakra Dam (Gobind Sagar)	1963	Satluj	Himachal Pradesh	PG	226	518	9,621,000	IH
Lakhwar	1990	Yamuna	Uttar Pradesh	PG	192	440	580,000	IH
Sardar Sarovar	1990	Narmada	Gujarat	PG	155	1,210	9,500,000	IHC
Tehri Dam	1990	Bhagirathi	Uttar Pradesh	TE, ER	261	570	3,539,000	IH
Thein Dam Ranjit Sagar (res.)	1990	Ravi	Punjab	ER, TE	160	565	3,280,000	IH
<i>Iran</i>								
Karoon	1975	Karun	Iran	VA	200	380	3,005,000	IH
<i>Italy</i>								
Alpe Gera	1964	Cormor	Adige Lombardia	PG	174	528	68,088	H
Place Moulin	1965	Buthier	Valle d'Aosta	VA	155	678	106,000	H
<i>Japan</i>								
Sakuma	1956	Tenryu	Aichi	PG	156	294	327,000	H
Ogochi	1957	Tama	Tokyo	PG	149	353	189,000	SH
Okutadami	1961	Tadami	Fukushima	PG	157	480	601,000	H
Kurobe	1964	Kurobe	Toyama	VA	186	489	199,000	H
Shirakawa	1964	Shirakawa	Gifu	ER	95	390	14,200	H
Tsuruta	1965	Sendai	Kagoshima	PG	118	448	123,000	CH
Taisetsu	1974	Ishikari	Hokkaido	ER	87	440	66,000	CHIS
Tedorigawa	1979	Tedori	Ishikawa	ER	154	420	231,000	HCSI
Naramata	1990	Naramata	Gunma	ER	158	520	90,000	CIS
<i>Malaysia</i>								
Kenyir	1990	S. Terengganu	Terengganu	ER	150	800	13,600,000	HC
<i>Mexico</i>								
Lazaro Cardenas (El Palmito)	1947	Nazas	Durango	TE	95	330	3,162,000	IC
Manuel Moreno Torres (Chicoasén)	1980	Grijalva	Chiapas	TE	261	485	1,613,000	H
<i>Paraguay</i>								
Itaipu	1982	Paraná	Brazil/Paraguay	ER/PG/TE	190	7,655	29,000,000	H
<i>Philippines</i>								
San Roque	1990	Agno	Pangasinan	ER	210	1,130	990,000	IHC

Dams, Classification, Table 3 (Continued)

Name of dam	Year of completion	River	State or province	Type (see note 1)	Height (m)	Crest length (m)	Reservoir volume (10 ³ m ³)	Purpose (see note 2)
<i>Romania</i>								
Gura Apelor	1984	Riul Mare	Hunedoara	ER	168	450	225,000	H
Pecineagu	1984	Dimbovita	Dimbovita	TE	105	270	68,900	SHI
<i>Russian Federation</i>								
Charvak	1977	Chirchik	Uzbek.SSR	ER	1,168	764	2,000,000	HI
Chirkey	1978	Sulak	Daghest. SSR	VA	233	333	2,780,000	HIS
Zeya	1978	Zeya	Amur	CB	115	758	68,400,000	HCN
Inguri	1980	Inguri	Georgian SSR	VA	272	680	1,100,000	HI
Nurek	1980	Vakhsh	Tadjik SSR	TE	300	704	10,500,000	HI
Sayano-Shushenskaya	1990	Yenisei	Krasnoyarsk	VA/PG	245	1,066	31,300,000	NH
Khudoni	1990	Inguri	Georg. SSR	VA	200	545	365,000	H
Rogun	1990	Vakhsh	Tajik SSR	TE/ER	335	660	13,300,000	HI
<i>Spain</i>								
Almendra	1970	Tormes	Salamanca	VA	202	567	2,649,000	H
Canales	1983	Benil	Granada	ER	159	340	71,000	IS
<i>Switzerland</i>								
Mauvoisin	1957	Drance de Bagnes	Valais	VA	237	520	181,500	H
Goescheneralp	1960	Göscheneralp	Uri	ER	155	540	76,000	H
Grande Dixence	1961	Dixence	Valais	PG	285	695	401,000	H
Luzzzone	1963	Brenno di Luzzzone	Tessin	VA	208	530	88,000	H
Mattmark	1967	Saaser Vispa	Valais	TE	120	780	101,000	H
Emosson	1974	Barberine	Valais	VA	180	555	227,000	H
<i>Turkey</i>								
Keban	1974	Firat	East	PG/ER	207	1,126	30,600,000	CH
Ayvacic	1981	Yesilirmak	North	ER	175	405	10,800,000	CH
Karakaya	1990	Firat	SE	VA	173	462	9,580,000	H
Altinkaya	1990	Kizilirmak	North	ER	195	604	5,763,000	ICH
Menzelet	1990	Ceyhan		ER	151	425	19,500	IH
Ataturk	1990	Firat	East	ER	184	746	48,700	ICH
<i>United States</i>								
Hoover (Boulder)	1936	Colorado	Nevada	VA	221	379	34,852,028	IHCN
Grand Coulee	1942	Columbia	Washington	PG	168	1,272	11,794,553	IHCN
Shasta	1945	Sacramento	California	PG	183	1,055	5,614,809	ISHN
Hungry Horse	1953	S. Fork Flathead	Montana	VA	172	645	4,277,715	IHCN
Swift	1958	Lewis	Washington	TE	186	640	932,512	HCR
Trinity	1962	Trinity	California	TE	164	747	3,019,563	IHCR
Cougar	1964	S. Fork McKenzie	Oregon	ER	158	488	270,463	HCIR
Glen Canyon	1966	Colorado	Arizona	VA	216	475	33,304,009	HSCR
Oroville	1968	Feather	California	TE	230	2,073	4,297,451	SCHR
New Bullards Bar	1970	North Yuba	California	VA	194	671	1,195,984	SH
Don Pedro	1971	Tuolumne	California	TE	173	549	2,503,968	H
Dworshak	1973	N. Fork Clearwater	Idaho	PG	219	1,002	4,259,213	HCR
New Melones	1979	Stanislaus	California	ER	191	475	2,960,356	CIHR
Bloomington	1981	N. Branch of Potomac	Maryland	ER	90	649	116,793	CSR
<i>Venezuela</i>								
Onia	1978	Onia	Mérida	TE	301	450	6,600	C
Yacambú	1990	Yacambú	Lara	TE	158	107	427,000	ICS

Note 1 – Dam types (see column 5): Earth TE, Rockfill ER, Gravity PG, Buttress CB, Arch VA, Multi-arch MV.

Note 2 – Purposes (see column 9): Irrigation I, Hydroelectric H, Flood control C, Navigation N, Water supply S, Mine tailings T, Recreational R.

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Cross-references

[Large Dams, Statistics and Critical Review](#)

DAMS, FLOOD PROTECTION, AND RISK

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The vital role of water

Our Earth has an abundance of water resources which is a fundamental factor in creating biological life and hence also human societies on this planet. On the other hand extreme hydrological events have always been a significant threat to human lives. Even the Bible tells us about the horror brought upon the ancient societies by the uncertainties of hydrology. We have always known that floods and droughts demanded some level of preparedness and coping strategies from society. Protection using levees, different land use depending on the season, and for instance floating houses all represent forms of coping with climatic variability related to flood events. Droughts were usually more problematic often leading to large-scale migration in order to cope with its harsh consequences. But water is more fundamental in our life than this. Ending poverty is often said to begin with water, clean water. Poor health, hunger, and lack of education are symptoms of the full scale of the true problem – including basic issues of availability of water of sufficient good quality.

Dams in the historical perspective

Dams and reservoirs have been used for thousands of years mostly as embankment dams in order to facilitate water storage primarily for water supply and irrigation and as water protection structures. At the same time hydrological variations in the river flows and water levels made it possible to irrigate flood plains. Water-dependant cultures and human civilizations developed in certain regions – Egypt, Mesopotamia, China, and India – where large rivers not only provided water resources but also due to the erosion and sediment transport capacity they

assured fertile soil deposits along the floodplains as a basis for agriculture. The oldest known earth dam was constructed as early as 3200 BC near the city Java in Jordan providing water supply to the city.

Many of these dams were built to protect populated areas and farmlands against devastating flooding events. The dams, often long systems of low embankment dams such as levees, dikes, and sometimes concrete or masonry structures as seawalls, often have to be combined with a drainage system in the protected area and pumping stations to handle local rain and water leaking into the protected area to maintain water balance in particularly lowland areas.

Dam safety

In all studies of water resources projects including water storage dams for water resources management and hence also flood and drought mitigation, the dam safety issue has to be considered. Water regulation and dam safety are closely coupled in a complicated way. An effective and safe use of water in the river system is normally based on water regulation by means of dams. A dam failure in the river system during an extreme high flow situation, particularly far upstream in the river, may then result in an additional dam break flood wave superimposed on the natural hydrological flood wave together propagating downstream, a severe situation that can cause other dams to fail further down in the system as a “domino effect.”

The dam owner has a responsibility for the overall performance of the dam. Dam safety is normally a strict responsibility in the sense that whatever the cause is of a dam failure and the following release of large volumes of reservoir water, the responsibility for the consequences to society has to be taken by the dam owner. This important responsibility cannot be delegated to someone further down in the organization. Different tasks related to maintaining a safe and effective dam performance can be directed to appropriate persons and levels in the organization that operates the dam and reservoir facilities. But the overall responsibility for the dam safety is always that of the dam owner.

Special roles are given to national authorities for the overall assessment of dam safety regulations as well as for regular supervision, inspection, and control of the dam safety status on a project level. Dams are classified according to risk perspective. Risk is then defined as the combined effect of probability for a negative event and its consequences. International and national associations collaborate to continuously update theoretical and empirical findings related to dam safety. A dam safety program should be developed and managed for every dam that can cause significant damage. The management of large dams and reservoir systems can benefit from being assessed by international dam expert teams as a means of an effective exchange of strategic dam management knowledge. A very challenging situation is dam construction in seismic areas. The most severe catastrophic events appear when a dam fails emptying the reservoir water

volume due to a combination of extreme high flows in the river system and an earthquake!

Perhaps the most important aspect of dam safety is a scientifically embedded and well-balanced knowledge base. Knowledge comprises both theory and practice. Dam design and construction, in all its elements and applications, in which climate issues and environmental impacts are key concepts, must be based on a scientifically sound knowledge base and make use of all the experience that may be documented in the form of best management practice.

Environmental and social impacts of large dams

The availability and use of water in water-scarce regions can be improved by means of water regulation dams and reservoirs for water storage. But particularly large dams can cause social and environmental damage if not properly designed and operated. Let us take just one example. The Narmada Valley Development Project in north-western India in the Narmada river system is a huge project with a number of large dams. The planning procedure as well as the way of mitigating negative social and environmental effects have been strongly criticized, particularly related to the two large dams Sardar Sarovar and Maheshwar. The Narmada Valley Development Project has been accused of violating several of the World Commission of Dams (WCD) guidelines with respect to the requirements set by the Commission particularly as related to a fair process for compensating project-affected people and a thorough analysis of alternatives as well as the absolute necessity of "Prior Informed Consent." WCD formulated these basic and important guiding principles in their report from 2000, "Dams and development – A new framework for decision making."

Integrated water resource and risk management

Sustainable water resources management emphasizes the need for an integrated and systems-oriented approach to balance different sector interests in the effective use of water resources as well as the minimizing of different risk perspectives particularly related to flooding and drought phenomena. Strategic water management then has to be based on multi-objective utilization of dams and reservoirs for water regulation of lakes and river systems.

Water resources management has a basic component of planning for utilizing available resources and hence also for effective preparedness of successful risk mitigation. The management strategies have two different elements: structural and nonstructural measures. Information, mainly with real time prediction systems, and public participation to increase awareness also improving the decision process, are essential parts of the risk mitigation. Dam design criteria and maintenance procedures also need to be continuously assessed and upgraded.

Systems engineering can be defined as an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed, that is, the application of engineering and systems analysis

to solutions of normally quite complex societal problems. The systematic matching of parts in the system encompasses subsystems, components, and modules that interact to produce specific objectives or results.

Applying risk management in this form, a number of basic perspectives have to be considered:

- Identification of risks and uncertainties and how they can be analyzed and evaluated
- Measures that have to be taken in order to reduce the risks to acceptable levels
- Development of systems that can be applied to provide a reliable understanding and control of various risks

Environmental impact assessment (EIA)

In the EU and also in other countries water directives require that an environmental impact assessment (EIA) is developed in the case of major infrastructure projects such as for water regulation dams. The purpose is to get an overall evaluation of the environmental as well as social impacts of the project before it is finally accepted. This assessment will be effective only as an integral part of an open and independent general discussion in society. A focus is on the planning process to actively involve "project-affected people." This is particularly important for projects with large dams and reservoirs that will cause resettlement of people due to inundation of water in the created water reservoir.

International collaboration

Many countries are dependent on water resources that originate upstream in other countries and therefore also controlled by these upstream countries. Actually more than 50% of the surface water resources in the world are shared by two or more countries. This can lead to political problems but also be a reason for international collaboration on the effective use of available water resources including more effective flood risk management. Another example is management of water scarcity when water-rich regions/countries can supply water-scarce regions/countries through water transfer systems of different types.

Floods and flood mitigation

Floods in rivers appear normally due to intensive precipitation as accumulated, superimposed flow components from different subcatchments in the drainage system. In steep river systems this may produce flash floods that are very concentrated and intensive local flow situations. A particular flooding problem follows a dam break when the reservoir water is emptied directly into the river drainage system.

Human societies have been interested in the use of flood plains since early times. Several benefits would arise from this utilization since in the flood plains the soil is fertile and the agricultural yield higher. Access to the river and river transportation was also easier. To reduce the problems of repeated periodic flooding it was necessary to develop structural alternatives to control extreme high

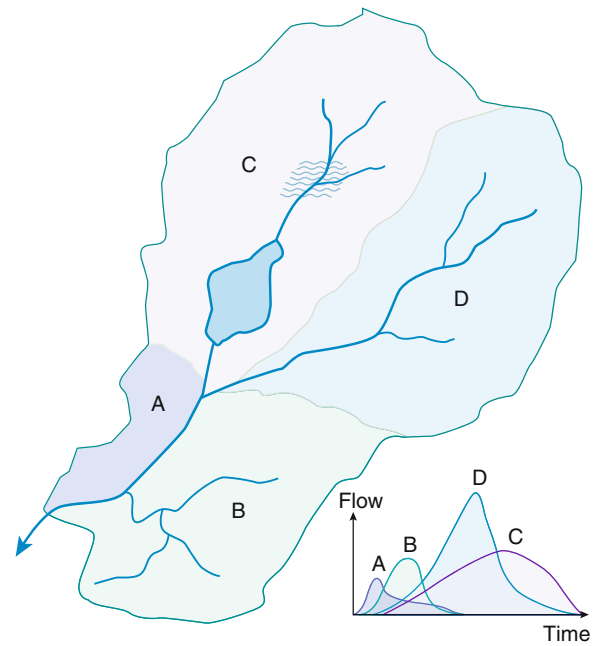
water levels. Levees and dikes are protecting land from flooding without essentially changing a flood wave that propagates downstream in the river. Flood mitigation schemes, however, should reduce the peak of the flood by the possible detention effects that can be achieved using the storage capacity that the reservoirs of these kinds of dam structures provide. Such retention of, for instance, seasonal high river runoff from a combination of precipitation and snowmelt in dam reservoirs requires very large storage volumes to significantly affect the runoff characteristics, particularly in the middle and lower parts of the river basin. A severe problem is sediment transport in the river system that can cause siltation of reservoirs and river branches and delta formations contributing to flooding. The huge High Aswan Dam in the Nile River has a water storage volume of the order of 150 km^3 whereas the annual sediment volume “trapped” in the reservoir is on the average about 1 km^3 which means that the practical service life of the High Aswan Dam project may be reduced to between 100 and 150 years due to sediment siltation problems.

Damages to economic assets resulting from natural disasters have increased significantly in the past say 20 years. Climate change will lead to intensified exposure to extreme weather conditions. Natural causes of the floods are related to rainfall intensity and its distribution, soil type and coverage, and several geomorphologic aspects of the watershed. Man-induced conditions may increase the risk of flooding, mainly deforestation, urbanization, unsustainable agricultural practices, and channelization/drainage and shifting of runoff pathways.

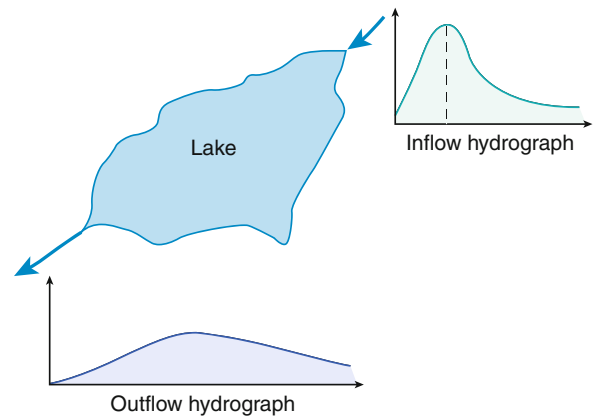
An important principle in more active flood mitigation is to spread apart in time accumulating flood components in different merging branches of a river system which will reduce the peak flow and associated water levels downstream and hence the risk for flooding. The situation when flow components accumulate in a branched river system and related problems of risks for flooding downstream is illustrated in [Figure 1](#). The principle of detention and flow peak reduction when a flow component following for instance a local rain storm is passing a natural, unregulated lake is demonstrated in [Figure 2](#).

Flow peak retention can be achieved also by creating more temporary storage capacity in the river system by, for instance, diverting water from the river into shallow flood mitigation reservoirs that can be localized in the landscape – “ecoflooding.” These detention storages must be effectively controlled hydraulically so that the temporarily stored water can be diverted back into the main river as soon as the flow capacity downstream allows that.

Multipurpose water management strategies that integrate flood control with hydropower production, water supply, irrigation, navigation, and environmental protection are of particular interest for many countries. This can also take the form of integrating dams, reservoirs, and detention basins for water diversion into the landscape and environment in order to reestablish a close and effective relationship between the river runoff system and local



Dams, Flood Protection, and Risk, Figure 1 Flow components accumulating downstream in a branched river system.



Dams, Flood Protection, and Risk, Figure 2 Natural retention and flow peak reduction following a flood wave passing through an unregulated lake.

communities to promote a more sustainable societal development. Multipurpose retarding basins in, for instance, Japan have been designed in addition to flood protection also to serve as centers of recreation including sport facilities and natural park areas.

Urban storm water management

In urban areas storm water management has to handle significant surface runoff since natural infiltration of precipitation is reduced due to the amount of impermeable surfaces that are typically found in urban environments.

This is as a result of pavement of streets and storm water arrangements that does not normally allow for natural infiltration processes. Storm water is often quite polluted and has to be treated before it is disposed to natural receiving water environments. To deal with storm water management in urbanized areas we have to develop what is often called “urban hydrology” providing more statistical and local information on intensive rains and modeling capacity for this type of rapid runoff processes.

Coastal protection systems

There are several large flood and coastal protection systems developed around the world. In the Netherlands more than one third of the land is located below sea level. During the devastating North Sea Flood of 1953, the levees and dikes that should provide protection against flooding failed at several critical points in the Netherlands killing almost 2,000 people and many more had to be evacuated. The Delta Works Project was implemented to prevent the recurrence of similar disasters. The Dutch Delta Commission is now responsible for the long-term strategic planning and implementation of the coastal defense considering climate change and alarming perspectives of significant long-term seawater level rise.

There are similarly a number of very severe floods on the *River Thames*. One of the worst floods on the nontidal, inner part of the river Thames occurred in 1894 following exceptionally heavy rains. In 1953, the combination of a north westerly storm and high tide caused a very high spring tide and the sea level to rise almost 3 m above normal spring tide level along the coast and the Thames Estuary with severe flooding as a result. This disaster initiated the construction of the Thames Barrier System.

Venice has a unique history and it is an important touristic center as one of the most beautiful water cities in the world. But Venice also has serious problems with flooding. Coastal flooding of the city with severe inundations of more than 90% of the City is becoming more frequent. Additionally to the inconveniences this is causing the City, intrusion of saltwater into the foundations of the buildings of Venice is a major problem threatening the cultural treasures of the City. To reduce the hazards to the City a flood warning system has been developed based on statistical and hydrodynamic modeling which will be a vital component also in the efficient operation of a storm surge barrier covering the three existing inlets to the lagoon of Venice.

St Petersburg, a beautiful water city, is with its five million inhabitants the largest City in the Baltic Sea Region. Since the very beginning St Petersburg had a variety of problems due to its localization in a marshy lowland area, particularly severe and relatively frequent flooding events caused by high flow situations in the river Neva, and simultaneously high water levels in the Finnish Bay. Another complicating factor is significant ice and snow jamming in spring time when the river is flowing through the complicated system of canals and natural river branches in St Petersburg out into the Finnish Bay.

The 25 km long flood control dam system at the old fortress Kronstadt is a huge project for protecting St Petersburg from high water levels in the Finnish Bay. It is soon to be completed, now with a more pronounced focus also on environmental and water quality aspects.

Stockholm is one of the most beautiful water cities in the Baltic Sea Region. The Lake Mälaren has its outflow to the Baltic Sea through the central parts of Stockholm by two short outflow branches embracing the Old City of Stockholm and ending into the inner part of the Stockholm Archipelago. Stockholm and Lake Mälaren have also significant flooding problems at the same time as the lake is an extremely important regional freshwater resource that has to be protected from saltwater intrusion. Sea level rise will ultimately reduce the capacity to handle the discharge of Lake Mälaren to the Baltic Sea making also the Subway system of Stockholm more vulnerable to the risk of water entering the subway from Lake Mälaren. Water has hence become a dynamic, strategic, and multidimensional component in the regional planning in the Stockholm – Mälaren region.

New Orleans is located at the delta formed by the huge Mississippi river system. The delta is instable since the marshy land area is subsiding and therefore depending on a steady sediment supply from the river. Tropical cyclones develop regularly in the Gulf of Mexico. Hurricane Katrina, August 23–30, 2005, had Category 5 with max wind speed 95 m/s when hitting the New Orleans area. This was the most devastating natural disaster in the history of the United States with almost 2,000 people that lost their lives in the storm and subsequent floods and material damages well in excess of \$100 billion. Approximately 80% of the New Orleans Metropolitan area was flooded with water depths exceeding 5 m in some areas. The consequences were a major breakdown in the social structure of New Orleans with hundreds of thousands displaced of which many have still not returned.

What went wrong? Primarily the following:

- The New Orleans *hurricane protection system* did not perform as a system!
- The *maintained design risk* for a 100-year storm event was inadequate.
- Flooding occurred when dikes/levees were overtopped but 4 of the 50 dike breakthroughs happened *before water levels reached the design levels*.
- *Pump stations were inoperable* due to lack of power supply and being not accessible for operators.
- The public did not appreciate the risk!

Not only Thailand but also Japan suffers regularly from major catastrophes caused by tsunamis. A tsunami is a well-known phenomenon appearing as a very long ocean wave generated by earthquakes or slides at the bottom of the ocean. The wave height is moderate in deep water but may pile up to a considerable height when reaching shallow coastal waters and it is therefore a major challenge to coastal protection systems in areas threatened by tsunamis. Effective tsunami warning systems in sensitive

coastal areas are absolutely necessary since these terrible waves propagate quickly to the coast very soon after initiation.

Extreme events of droughts

Long periods of drought often lead to population migration. Several areas in the world today are under the threat of severe drought, both in the developed and developing world, such as parts of Australia, East Africa, India, China, Pakistan, Nepal, Myanmar, and many other countries. Periods of drought can cause significant environmental, agricultural, health, economic, and social losses. Rainfall variability at a timescale from years to days is as much a characteristic of climate as the total amounts recorded. Agricultural drought occurs when water supply is insufficient to cover crop or livestock water requirements. Much more than the occasional widespread and severe climatological droughts which catch the attention of the media, it is this “invisible” agricultural drought which prevents farmers at the subsistence level from achieving regular and high yields. Such drought is caused by environmental degradation as much as by climate. Drought losses are not as easily accountable as flood losses, mainly due to their length of occurrence, but they also represent a heavy burden to society.

In April 2008, a combination of drought, failed harvests, and the continued rise in global food prices left millions of people facing hunger in Ethiopia, Kenya, Somalia, and Somaliland. In Ethiopia, the government estimated that close to five million people were in need of emergency food aid. Areas which normally get two rainy seasons a year have had inadequate rain for more than 12 months. Crops failed, livestock have been dying. In northern Kenya, Tangelbei division and the larger part of Baringo district had serious food and water shortage, causing the deaths of vital livestock. Food security in this area was deteriorating and further complicated by rising food prices.

Climate change and sea level rise adaptation

Preparing for the accelerating increase in sea level that will take place in the future as a result of global warming and glacial ice sheet melting is very much needed. The reports from the Intergovernmental Panel on Climate Change (IPCC) are comprehensive documents summarizing the impact of global warming on the planet. But they are not without deficiencies, and one of the most notable was the analysis of future sea level rise contained in the Panel report from 2007. Given the complexities of forecasting how much the melting of the Greenland and West Antarctic ice sheets will contribute to increases in global sea level, the IPCC did not include these huge ice masses in their calculations, ignoring what is likely to be the most important source of sea level rise in the twenty-first century.

The serious threat posed by rising sea levels is obvious, especially since there is evidence from the past 2 years of the accelerated melting of the Greenland and West Antarctic ice sheets. The consequences of a major sea level rise are

massive. Coastal erosion and land retreat will increase at many locations. Agriculture will be disrupted, water supplies will be degraded by saltwater intrusion, storms and coastal floods will reach further inland, and millions of environmental refugees will be created – 15 million people live at or below 3 ft. sea elevation in Bangladesh, for example. Governments, especially those in the developing world, will have additional severe problems.

The most vulnerable of all coastal environments are deltas of major rivers, including the Mekong, Irrawaddy, Niger, Ganges–Brahmaputra, Nile, and Mississippi. Here, land subsidence will combine with global sea level rise to create very high rates of what is known as “local, relative sea level rise.” Rising sea levels may displace a vast majority of people in these delta regions. The city of New Orleans can probably be protected into the next century, but only at great expense and with little guarantee that future storms like hurricane Katrina will not inundate the city again. The world’s major coastal cities undoubtedly receive most of the attention as sea level rise threatens infrastructure. Miami is the most endangered city in the world measured by the value of property that would be threatened already by a 3-ft. sea level rise.

Concluding remarks

Dams and reservoirs in river systems provide the fundamental basis for more effective use of water resources. A special emphasis is in this context on the development of multipurpose water regulation strategies for well-coordinated use of the different water storage reservoirs in the system to properly balance a variety of possible interests in water resources management. Hence, the variability of the river runoff components in the catchment can be handled by using the storage capacities that the dam reservoirs provide for more stable water supply and irrigation needs and also for very often quite important hydropower production.

This is particularly essential for managing risk problems in the river system related to both flooding and drought situations. However no damping can be achieved in the river system locally and downstream in an extreme high flow situation if the reservoir storage is full at that time – there is no free or “live” volume in the reservoir for flow detention and no water can be drawn from the reservoir if the reservoir is empty in a similar drought situation. The degree of water regulation seen, for example, as a ratio of available storage capacity upstream a certain point in the river system relative to the corresponding value of the mean annual runoff should for hydrological conditions applicable to for instance northern Europe be of the order of 0.3 to enable an effective use of water all year around. This regulation degree will not be sufficient in most subtropical and tropical climates. Additionally and most important, more dynamic water regulation strategies based on both short and long-term meteorological and hydrological weather and runoff predictions are required for implementing effective water resources management systems.

The complexity of applying systems-oriented water resources and risk management for river systems is obvious. Increasing problems with water scarcity can be related to both global population growth and climate change effects. Predicted sea level rise indicates significant new challenges for coastal protection. Also here flood barriers and different dam structures are needed. The strategies for creating sustainable water infrastructure systems have to comply with a set of engineering, economical, social, as well as environmental assessments and constraints within the framework of the specific projects. Probably the most important perspective is about democracy! Particularly large-scale water resources dam projects have to be planned and implemented in such a way that everyone benefits from the project – everyone from “project-affected people” locally to all those living in regions and countries involved.

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DEAD SEA

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Synonyms

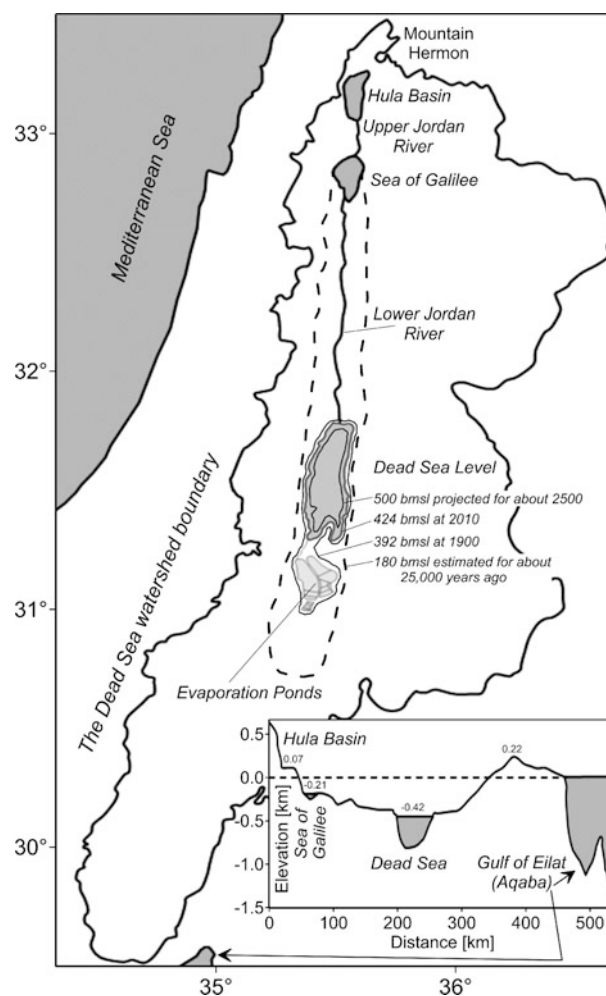
Al-Bahr al-Mayyit – the Dead Sea (Arabic); Sea of Asphaltites – (Attic Greek); Yam Ha-Mavet – the Dead Sea (Hebrew); Yam Ha-Melah – the Salt Sea (Hebrew)

Definition

The Dead Sea is a terminal hypersaline lake situated in the land lowest depression of the Jordan Rift Valley between Arabian and Sinai tectonic plates.

Introduction

During the late Pleistocene, the Arabian and Sinai plates were separated by the Dead Sea precursor – Lisan Lake which covered the Jordan Rift Valley entirely about 25,000 years ago. The surface level at that time was about 180 m below mean sea level (bmsl). The modern Dead Sea was formed as a result of recession in the Lisan surface level about 10,000–14,000 years ago (Oren, 2003). Until the beginning of the twentieth century, the seawater level underwent natural fluctuations from about 380 to 420 m bmsl which were associated with interannual variability of precipitation in the Levant region (Kushnir and Stein, 2010). Since the early 1960s, anthropogenic reduction in the Dead Sea freshwater budget outweighed its natural variability because of the countries controlling the freshwatershed of the Dead Sea (i.e., Israel, Syria, and Jordan, Figure 1) increased the water consumption intensively.



Dead Sea, Figure 1 The Dead Sea watershed. Insertion shows profile along the Jordan Rift Valley toward Gulf of Eilat (Aqaba). (Adopted from Niemi et al., 1997.)

Moreover, Israel and Jordan use the Dead Sea water for the production of minerals, contributing to the water deficit. As a result, sea level decreases rapidly (Niemi et al., 1997). Until 1978, the morphology of the Dead Sea consisted of a large and deep northern basin and a smaller and shallower southern basin connected via the Lynch straits (Neev and Emery, 1967). Following the recession of the water level, the entire southern basin would have dried up. However, dikes were erected to transform the southern basin into evaporation ponds for mineral production. During the period 1996–2010, the northern basin surface level decreased at a rate of 1 m/year, and the area shrunk with a rate of $\sim 2.4 \text{ km}^2/\text{year}$. In 2010, the Dead Sea dimensions were: surface level $\sim 424 \text{ m bmsl}$, maximal depth $\sim 295 \text{ m}$, area $\sim 609 \text{ km}^2$, volume $\sim 130 \text{ km}^3$, maximal north-south extension $\sim 50 \text{ km}$, and maximal west-east extension $\sim 16 \text{ km}$. Water salinity was $\sim 280 \text{ g/kg}$, and water density was $\sim 1,240 \text{ kg/m}^3$ at 25°C .

Water budget

During the drought years 1996–2010, the major source of freshwater was still the lower Jordan River: $60\text{--}150 \times 10^6 \text{ m}^3/\text{year}$. The total freshwater inflow (including precipitation and floods) was $265\text{--}335 \times 10^6 \text{ m}^3/\text{year}$. Evaporation rates derived from energy budget were 1.1–1.2 m/year. The low evaporation rate of Dead Sea, compared with fresh lake in similar conditions (1.4–1.5 m/year for the Sea of Galilee, Rimmer et al., 2009), is connected with the high hygroscopic ability of the Dead Sea brine (Krumgalz et al., 2000; Lensky et al., 2005). The total water deficit of the lake is $690 \times 10^6 \text{ m}^3/\text{year}$. About 36% of this amount is due to the activity of the chemical industries in the southern basin of the Dead Sea (Lensky et al., 2005).

Meteorology

The climate in the Dead Sea area is highly arid, with a mean annual rainfall less than 100 mm (Goldreich, 1998).

Air temperature over sea has been observed between 7.5°C and 43.4°C . While typical relative humidity over the Dead Sea is between 33% and 52%. On average, August is the hottest month with air temperature of 33°C and July is the driest (39% humidity). The coldest and most humid month is January with an average temperature of 18°C and 47% humidity. Air temperature changes are closely associated with the arrival of the Mediterranean breeze as well as with the onset of the local breeze. The daily maximal temperature occurs 4 h later than along the Mediterranean coast.

The atmosphere above the sea surface differs from that on land. Air temperature above the sea is colder by about $0.5\text{--}1^\circ\text{C}$ during summer and warmer by about $1\text{--}2^\circ\text{C}$ during winter. Relative humidity above sea is higher by about 4–5%.

Air pressure at the Dead Sea surface is higher than at the mean sea level by about 50 mb.

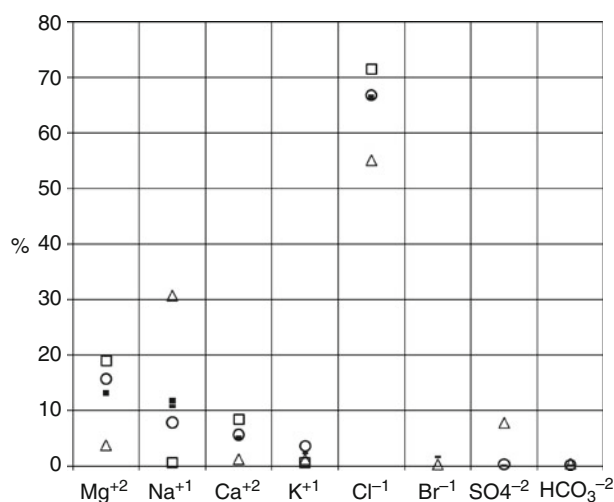
The typical speed of winds is 4–6 m/s. In general, during summer, winds are mostly northerly. During winter, there is an increase in the southerly winds. During winter, strong winds (10–20 m/s), although rare, occur more frequently than during summer. Westerly winds, associated with the Mediterranean breeze, occur at the same rate throughout the year. They appear in the late afternoon and can reach 20 m/s at midnight. Wind strength diminishes in the morning with the weakest winds occurring around 13:00 (Hecht and Gertman, 2003).

The maximal wind wave heights observed were at 3 m with 8 s period (Hecht et al., 1997).

Chemical composition

The salinity of the Dead Sea water is about eight times larger than that of oceanic water, being supersaturated in respect to halite and perhaps other minerals. Dead Sea water has a particular ionic composition, which is dominated by magnesium chloride unlike oceanic water which is dominated by sodium chloride (Figure 2). The extremely high salinity of the Dead Sea water as well as its unique ionic composition prevents the implementation of inexpensive methods of ocean water salinity measurement. Therefore, in order to characterize the Dead Sea haline structure and variability, one uses its density anomaly from $1,000 \text{ kg/m}^3$ at 25°C (Anati, 1997). This is defined as quasi-salinity.

Since the early 1980s, massive amounts of halite have precipitated from the water column as halite crystals (Gavrieli, 1997). A subject submerged in the Dead Sea water with temperature below 25°C is covered by halite crystals (Figure 3).



Dead Sea, Figure 2 Percentage of ionic concentrations in the Dead Sea water. Δ – ocean water, $\circ$ – Dead Sea water during 2008, $\blacksquare$ – Dead Sea water during 1960–1996, $\square$ – end brines from evaporation ponds. (Data derived from Steinhorn (1981); Gavrieli (1997), Oren (2003), Gertman et al. (2010).)



Dead Sea, Figure 3 Halite crystals accumulated during 2 months on the equipment submerged from the Dead Sea meteorological buoy.

The Dead Sea water ionic composition is unstable due to halite precipitation as well as the water exchange with the evaporation ponds. The Dead Sea water from the northern basin is pumped into the evaporation ponds, where halite continues to precipitate until the salt contents reach some composition when carnallite ($\text{KMgCl}_3 \cdot 6(\text{H}_2\text{O})$) starts to precipitate. The latter is the targeted mineral which is used for potash production. The wasted residual water (about 50% from the pumped volume) is returned to the Dead Sea with a relatively high content of Mg–Ca–Cl (Gavrieli and Oren, 2004).

Hydrology

For hundreds of years the Dead Sea was a meromictic lake (see *Meromictic Lakes*) with stable haline stratification, supported by runoff. Winter convection was limited, and water below the halocline was not affected by atmosphere. As a result of the runoff reduction, the upper-mixed layer (UML) salinity increased, and the gravitational stability diminished. Eventually, during the winter of 1978–1979, the lake water overturned, ending the long-term stable hydrological regime (Steinhorn and Gat, 1983; Anati, 1997). Since then, the lake entered a new phase in which its hydrological regime is either holomictic or meromictic. Since 1979, the meromictic regime is

established twice only after extremely rainy winters: during 1980–1982 and during 1992–1995.

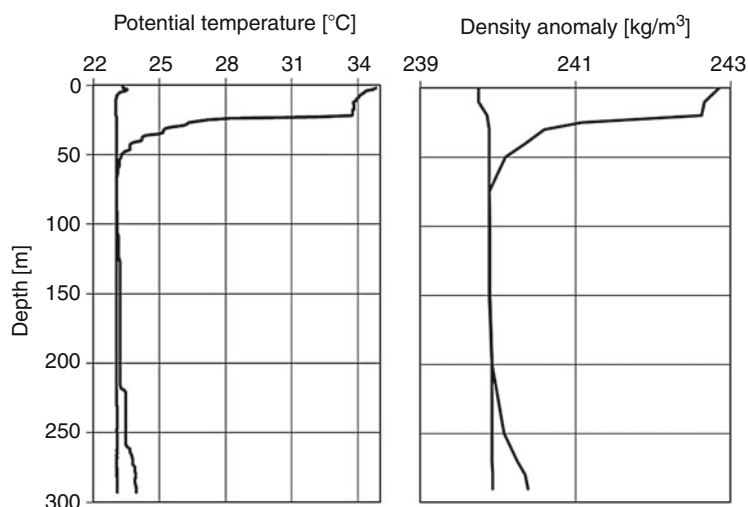
Regardless of regime, deep water temperature remains in the range 22–24°C, while quasi-salinity has increased since 1978 from 232 kg/m³ at a rate of ~0.35 kg/m³ year (Anati, 1997; Gertman and Hecht, 2002). Seasonal thermocline is formed in the middle of March. UML during meromictic winter has low quasi-salinity (200–210 kg/m³) and can be colder than the deep layer due to hydrostatic stability which limits winter convection (e.g., in winter 1993, temperature dropped to 15°C (Beyth et al., 1993)). During summer, the UML reaches maximal temperature (32–35°C), and quasi-salinity value is ~3 kg/m³ higher than at the deep water. The UML thickness during meromictic periods and holomictic summer fluctuates between 15 and 30 m. Convective mixing of the entirely water body occurs during the second half of November in the holomictic regime (Figure 4).

Extremely hot and dense water (up to 44°C and 1,350 kg/m³, Lensky et al., 2005) entering in the southern part of the Dead Sea from the evaporation ponds propagates as gravitation currents northward following the bathymetry. During the summer, this water forms a bottom layer in the entire deep region. The layer is warmer (~0.5°C) and saltier (~0.5 kg/m³) than the main water body layer above it. Double diffusion builds step-like profiles of water properties in the bottom layer (Gertman and Hecht, 2002).

Expected future of the Dead Sea

The sea surface level is expected to decrease in the course of the nearest 500 years. However, some deceleration of the sea level decent has been predicted by different models even if the runoff and industrial water consumption will not change in the future (Yechieli et al., 1998; Krumgalz et al., 2000; Asmar and Ergenzinger, 2002). In all the models, the evaporation rate is inversely proportional to the concentration of ions. Moreover, the integral evaporation decreases with the sea surface area decrease. A critical ionic concentration will diminish the evaporation dramatically when the sea level reaches ~500 m bmsl.

Several proposals were made for stabilizing the Dead Sea water level by connecting the Dead Sea with the Mediterranean or the Red Sea. The main idea is to utilize more than 400 m difference in sea levels to generate hydroelectric energy. Additional profit can be achieved due to desalinization of the seawater on the way to the Dead Sea. In 2005, the governments of the Israel, Jordan, and the Palestinian territories supported by the World Bank agreed to conduct a feasibility study for a canal or pipeline between the Gulf of Aqaba and the Dead Sea along the Arava Valley transporting initially Red Sea water and eventually high salinity end brines (by-product of desalinization) into the Dead Sea. The most evident problems concerning this proposal are: restoration of meromictic stratification, mass precipitation of gypsum, and development of new life-forms (Oren, 2003).



Dead Sea, Figure 4 Vertical profiles of potential temperature (*left panel*) and quasi-salinity (*right panel*) in the deep region of the Dead Sea during February and August 2009.

Summary

For hundreds of years prior to 1950, the Dead Sea surface level was about 400 ± 20 m bmsl. During this period, dilution of the upper layer by the freshwater runoff was sufficient to support stable stratification even during the winter seasons. Anthropogenic reduction of runoff and water consumption for industrial mineral production led to significant changes in dimensions and hydrology of the Dead Sea. Israel Dead Sea Works Ltd. and the Jordanian Arab Potash Co. pump water from the northern part into industrial evaporation ponds located where the southern part used to be. After the extraction of potassium and bromide salts, the remaining extremely dense water is returned to the northern part. During 1978–2010, the northern part sea level descended by 23 m, the area shrank by 58 km^2 , and the volume decreased by 15 km^3 . Gradual salinity increase in the upper layer led to the first overturn in winter 1978–1979. Stable haline stratification, preventing winter overturns, was restored twice after extremely rainy winters of 1980 and 1992, and lasted for 3–4 years each time. The main body water density increased since 1979 from $1,232 \text{ kg/m}^3$ to $1,241 \text{ kg/m}^3$ due to increased ionic concentration. Halite is saturated since about 1980, and permanent precipitation is observed on submerged objects. Increase of ionic concentration leads to decreased evaporation rate; therefore, sea level drop rate is expected to decrease in the future. Different estimates of the future Dead Sea water budget came to a common conclusion that in about 500 years, the sea level will be ~ 500 m bmsl.

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[Meromictic Lakes](#)

DELTAIC SWAMPS

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Definition

A delta is formed where the mouth of the river flows into an ocean, sea, desert, or lake, or simply into a swamp. It is characterized by the main channel dividing into multiple streams or “distributaries.” The water balance of deltaic swamps has some special features differing from usual river basins, reservoirs, and lakes. The main differences are the variable area of swamps and the unsteady flow distribution. A river basin is usually well defined, and the area, for practical purposes, is constant. But in a swamp, the area changes continuously in response to inflow, precipitation, and evapotranspiration. These, in turn, themselves, vary during the year and from one year to another.

Deltaic swamps: examples and description

A well-known example of a deltaic swamp is the Okavango Delta in Botswana. A peculiarity of the Okavango Delta is that the outflows are a very minor fraction of the total input (inflow plus precipitation) due to the evapotranspiration losses from the large area. The outflow appearing in the Boteti River, for example, amounts to only about 2% of the input. Thus, predication of outflow from the Delta is not as easy as from river basins generally.

In addition to this, the flow distribution of the Delta, though partly controlled by vegetation, seems to change in response to earth tremors. Much attention has, in the past, been paid to blockages of the Delta channels by floating plant material. From a boat, these blockages seem dramatic, but we now know that the bulk of flow through the swamps takes place outside the open water channels. It seems to follow that channel blockages are not, in themselves, the main or most immediate agents of change in the distribution of flow.

Scattered throughout the delta are thousands of islands, the number actually estimated at about 50,000, each island being unique in the types of trees it supports (jackalberry, mangosteen, knobthorn, date palm, and fig). Most of the smaller islands have been formed by the fungus-growing termites, and their activity not only raises patches of land above the flatness of the Kalahari but also enriches the soil.

The Delta’s wildlife includes lions, leopards, elephants, buffalo and rhino, cheetah, giraffe, hippopotamus as well as antelopes, zebra, buffalo, baboons, monkeys, hyenas, and crocodiles.

The celerity of the flood wave through the Delta from Mohembo to Maun is of the order of 5 cm/s. Electrical conductivity measurements of the swamp waters show that the average velocity of flow is even less than this. Such slow movement indicates that most of the flow takes place through the swamps outside the main channels although these swamps might have been assumed to be already “blocked” by vegetation.

Observations and simple calculations of water balance show that the area of the swamp is at its maximum during the months of June and July and reaches its minimum in December and January.

Deltaic Swamps, Table 1 Worldwide distributed large deltas

Name	Area in km ²	
Amazon	467,000	Brazil
Chao Phraya	11,000	Thailand
Danube	2,700	Romania
Ebro	600	Spain
Ganges-Brahmaputra	106,000	Bangladesh/India
Huang	36,000	China
Indus	40,000	Pakistan
Irrawaddy	21,000	Burma
Lena	30,000	Russia
MacKenzie	13,500	Canada
Mahakam	5,000	Indonesia
Mekong	94,000	Vietnam
Mississippi	29,000	USA
Nile	15,000	Egypt
Niger	19,000	Nigeria
Orinoco	20,000	Venezuela
Po	13,400	Italy
Rio Grande	8,000	USA
São Francisco	700	Brazil
Senegal	4,300	Senegal
Yangtze	66,700	China

After entering the Delta, the water spreads out over an area of the cone which varies according to season and from which evaporation and transpiration (considered as one item – evapotranspiration) takes place.

As the water level rises and falls and the area increases in response to changes in inflow and to rainfall and evapotranspiration, so the amount of water in storage will change. We therefore come to the basic equation for the Delta as a whole and for each part of it:

$$\text{Inflow} - (\text{Evapotranspiration} - \text{Rainfall}) \\ \times \text{Swamp Area} - \text{Increase in Storage} = \text{Outflow}$$

Some examples of worldwide distributed large deltas are given in [Table 1](#).

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[Amazon Lakes](#)
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[Asia, Lakes Review](#)
[Australia, Coastal Paleolakes of "Swanland"](#)
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DEW PONDS

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Definition and introduction

The subject of dew ponds is one of perennial interest after more than 200 years of research since Gilbert White noticed the phenomenon of upland ponds in southern England and the Yorkshire area where one pond only leaked once in 400 years and only did so because roots of rushes penetrated the clay.

Dew ponds are artificial, saucer-shaped depressions commonly found on upland surfaces in northwest Europe, most notably in southern England. They are used to provide convenient small-scale watering sources for sheep

and cattle in otherwise dry areas. Large-scale domestication of these animals began in Africa during the late Paleolithic, and following the end of the last ice age, animal husbandry accompanied human immigration into northwest Europe during the Mesolithic (around 8000 BC) and especially in the Neolithic (5000–2000 BC). During the nineteenth century, however, the widespread extension of piped water supplies caused dew ponds to fall into disuse. In the late twentieth century, however, a sociological trend toward a simplification of life systems has led to the revival of the old facilities (see [Figures 1](#) and [2](#)).

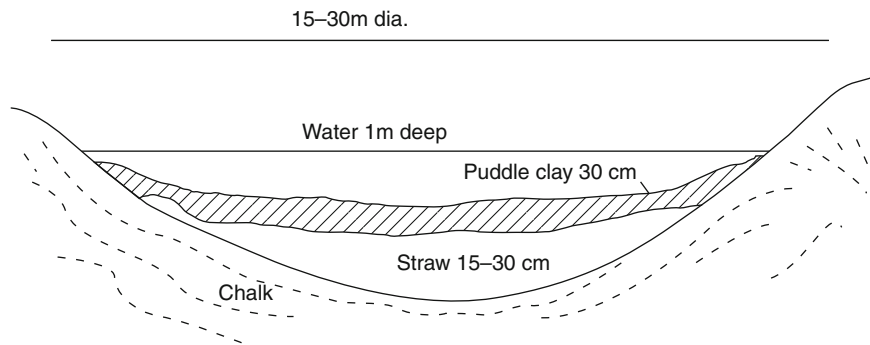
The dew pond is still important today particularly in the high chalk country of Surrey, Sussex, Kent, and Wiltshire in southern England. It is a fact that the ponds rarely run dry, and this was confirmed by local farmers to the author on a visit to study the ponds.

Construction

The ponds are normally saucer-shaped, about 15 m in diameter, and 1 m deep at the center usually with a substantial catchment of some 30-m diameter. To be classed as a dew pond, except for its own natural catchment, there should be no ingress of water from springs, channels, or any form of drainage into the pond. The essential ingredient of the dew pond is a completely waterproof layer of puddled clay, usually of about 30 cm thick, over a 30-cm layer of straw ([Figure 1](#)). The clay is not allowed to dry out and crack and hence break the seal. At the turn of the twentieth century, the puddling of the clay was often done by oxen but today puddling is performed by caterpillar tractor. Otherwise, construction methods have changed little over the centuries except that, when a pond is restored, a butyl rubber or polythene liner is sometimes used between the straw and the puddled clay layer (Belden 1997, Private communication and discussion, Sussex Downs Conservation Board; Larkin, 1997, Private communication and discussion, Brighton and Hove Environmental Services).

Restoration of ancient dew ponds in southern England is in progress today, with the support of various environmental groups, notably the Sussex Downs Conservation Board and the Brighton Environmental Services. Using old maps, these organizations inspected over 230 possible sites where dew ponds were known to have existed at one time. From the survey, only 68 sites proved to be genuine dew ponds, of which 40 still held water, but only 14 were being used for stock watering (Carpenter, 1995). [Figure 2](#) shows one of a selection of the 30 dew ponds restored to date. Today, for the interested including tourists, information is displayed, in the form of a notice, giving some notes on dew ponds for the public's information throughout the South Downs at selected dew ponds.

Although [Figure 1](#) shows one method of construction of a dew pond and although it is basically the method adopted in the restoration of ponds today, it has not been the only one in the past, and over the last two centuries, there have been several variations, depending mainly on the part of



Dew Ponds, Figure 1 Cross-section of a typical dew pond.



Dew Ponds, Figure 2 Dew pond in Shoreham, England.

the country in which the dew ponds were constructed. Martin (1915, 2002) shows that straw and puddled clay were used in one position or another and often in a series of layers of (from the bottom) straw, clay, straw, clay, straw, and clay (giving six layers); clay, straw, and chalk rubble; quicklime, clay, quicklime, straw, and broken chalk; chalk puddle only; straw, clay, and stones; and lime-tempered clay, straw, and loose rubble or broken chalk.

History

It is believed that dew ponds date from prehistoric times, possibly from the Neolithic or even Paleolithic periods. In both of these periods, the water table on the chalk of the Sussex Downs was probably much the same as it is today. The ponds were to be found high up in the Downs

where stock required to be watered rather than exposing them to a long trek down to the valleys below.

Gilbert White, the naturalist, mentions the ponds in his writings in 1776 when he noted that:

the little ponds on the chalk hills were not known to fail even when ones in the vales were dried up. White wrote: Now we have many such little round ponds in the district [Selborne]; and one in particular on our sheep-down ... [contains] perhaps not more than two or three hundred hogsheads of water [300 hogsheads = 73,000 litres] yet never is known to fail, although it affords drink for 300 or 400 sheep and for at least twenty head of large cattle besides; and in spite of evaporation from sun and wind, and perpetual consumption by cattle, yet [these ponds] constantly maintain a moderate share of water, without overflowing in the wettest seasons, as they would do if supplied by springs. By my journal of May 1775, it appears that the small and even considerable

ponds in the valleys are now dried up, while the small ponds in the very tops of hills are but little affected. Can the difference be accounted for from evaporation alone, which is certainly more prevalent in bottoms? or rather, have not those elevated ponds some unnoticed recruits, which in the night-time counterbalance, the waste of the day, without which the cattle alone must soon exhaust them.

Clearly, White was intrigued by the ponds, and did he too think of dew supplementing them by night but was too professional to say so?

Theory

Dew consists of drops of water, the condensation of atmospheric water vapor on any surface where the temperature has fallen below the dew point. The latter is defined as the temperature at which the saturation pressure equals the vapor pressure. If the ambient temperature is below 0°C, it becomes the frost point. A dew point hygrometer may be used to determine surface dew point. More often, dew point is simply determined with a psychrometer (wet and dry bulb thermometer).

Dew is often the only source of water available for plants and animals in desert regions. In northwest Europe, dry areas exist, especially on the Upper Cretaceous chalk formation (widespread in southern England, northern France, and Germany) which is homogeneously porous and consequently well drained, even though there is abundant rainfall (750–1,000 mm). Thus, there is a genuine need for dew ponds. However, the term is based on a misleading deduction, dating from antiquity. Walford (1924) reported it as “the great dewpond myth.” Alas, the maximum experimental dew accumulation is only 50 mm year⁻¹. Earlier experiments noted by Pugsley (1939) were carried out by Slade (1877), Hubbard and Hubbard (1904), and by Martin (1915), but all led to the same conclusion. Nevertheless, the term enjoys the priority of antiquity and is therefore permanently established.

The explanation is that in a region of annual precipitation up to 1,000 mm, rather evenly distributed throughout the year as a rule, and where the annual evaporation is only 450 mm, there should be an abundant water supply except in major drought cycles (as in 1994–1997, the driest in centuries). However, there are often cases where the least rainfall occurs when there is the greatest evaporation. In these cases, mists and fogs may account for filling the ponds. There seems scope, however, for further research. Slade (1877) notes that “shepherds reported that some dewy nights had added 2.5 cm to the water measurement of the afternoon before.” Nevertheless, the meteorological setting is significant. In a region of prevailing westerlies, the often nearly saturated humid air mass is forced to rise 200–300 m as it encounters the Downs, where the air temperature may fall below the dew point and a “scotch mist” may result.

Conclusion

The principle, construction, and operation of dew ponds still invite interest today in understanding them. One

may often hear the view that “dew can never feed a pond; it is formed from the moisture in the air being in contact with the cooled earth’s radiation at night.” Researchers have spent night after night on the banks of ponds watching for dew being formed even on the banks often without success. Yet a young farmer told the author that in his time and his father’s and grandfather’s time, the farm dew pond had never been depleted.

Many studies have been carried out into dew ponds since Gilbert White’s work in 1775 in Selborne, England; but, work still continues, although today the dew ponds are mainly artificial, and many are constructed for the tourist’s pleasure. However, some of the original English dew ponds still in operation are reputed to go back in time to Early Man.

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Cross-references

Transboundary Waters: Rivers, Lakes, and Groundwaters

DISSOLVED OXYGEN IN ICE-COVERED LAKES

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Definition

DO deficit is a difference between the actual amount of dissolved oxygen in lake or sea water and the saturation concentration at the temperature of the water mass sampled.

Oxygen depletion is a phenomenon that occurs in aquatic environments as dissolved oxygen becomes reduced in concentration to a value detrimental for aquatic organisms living in the system. It may provoke formation of a so-called “dead zone.”

Dead zone is an anaerobic area in a water body where existence of majority of aquatic organisms is impossible.

Fish kill also known as *fish die-off* and as *fish mortality*, is a localized die-off of fish populations which may also be associated with more generalized mortality of aquatic life. The most common cause is reduced oxygen in the water.

Under-ice warming is the increase of water temperature during the ice-covered period that occurs mainly in shallow (up to 10–15 m in depth) water bodies due to heat inflow from sediments.

Introduction

One of the main parameters, which allow to assess the lake water quality, is dissolved oxygen (DO). The evolution of the oxygen regime in the lakes is usually controlled by the following processes: (1) gas exchange through the water–air interface; (2) vertical turbulent mixing within a water column; (3) photosynthesis that contributes the increase of DO concentration in water; (4) respiration of water organisms, bacterial oxidation of organic matter, chemical oxidation of H_2S , Fe^{2+} and other reduced inorganic substances leading to a decrease of the DO content in water; and (5) oxygen uptake by bottom sediments. During the period of open water, the upper layer of a lake (epilimnion) is, as a rule, well saturated due to the permanent gas exchange between water and atmosphere. In lower layers, seasonal DO dynamics is determined by the vertical turbulent mass transfer and biochemical consumption. In winter, when a lake is ice covered and isolated from atmosphere, intensive vertical mixing and photosynthesis are practically absent; therefore, the oxygen uptake due to biochemical destruction of organic matter in water and in sediments may lead to the oxygen deficit there, sometimes to its complete depletion and to the development of the fish kill effect (Barica and Mathias, 1979; Greenbank, 1945; Hargrave, 1972; Hutchinson, 1957). As the ice-covered period in boreal lakes lasts for 180–190 days, this, in turn, may endanger the whole lake ecosystem.

The winter DO regime phenomenology

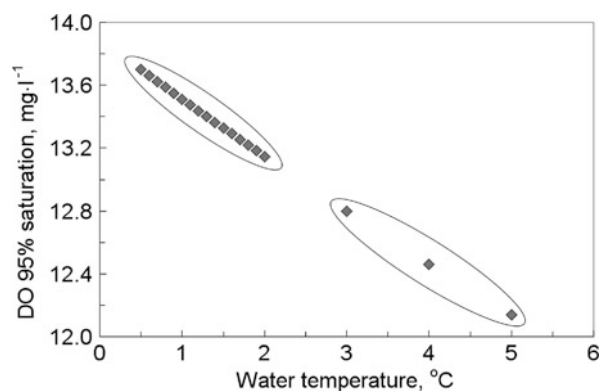
Let us consider conditions in a shallow lake before the ice-covered period starts. The water column is well chilled and rich of DO (about 94–96% of saturation, see, e.g., Terzhevik et al., 2009) due to heat loss into the atmosphere and strong wind mixing. If biological productivity of a lake is low and amount of newly formed in autumn organic matter (OM) is negligibly small, DO content varies depending on water temperature and is consumed only in the very vicinity of bottom due to bacterial activity. Hutchinson (1957) suggested an empirical relation to roughly estimate the saturation DO value C^* as a function of water temperature T ,

$$C^* = 14.6221 - 0.407699T + 0.00812934T^2 - 0.000079448T^3 \quad (1)$$

which allows to calculate 95% values for the whole range of water temperatures typical for ice-covered lakes (Figure 1).

In real life, this hypothetical case practically never occurs. All lakes are affected, to greater or lesser extent, by inflow waters coming from their catchment areas and by human activities, which can be considered as sources of nutrients and provoke lakes bioproductivity. Depending on its amount, newly formed OM, stored in near-bottom layers of local deepenings and upper layers of sediment, may cause DO consumption because of its bacterial destruction that leads to the formation of DO deficit or depletion.

Roughly speaking, one may distinguish four stages of the winter DO regime. The first stage precedes the ice cover development and can be called “winter cooling.” On the background of water cooling, the newly formed in autumn OM sinks toward a lake bottom, being heavier than surrounding water. Depending on heat loss and wind mixing, the length of this stage varies and affects the DO content – the longer former, the higher latter. Thus, the first



Dissolved Oxygen in Ice-Covered Lakes, Figure 1 DO values of 95% saturation corresponding to the initial water temperatures (upper left part, 0.5–2°C) and to the bottom water temperatures within a period of under-ice warming by heat transferred from sediments (lower right part, 3–5°C) typical for shallow ice-covered lakes.

stage is a prerequisite for the DO deficit/depletion development.

The second stage starts after ice cover formation and can be characterized by DO consumption throughout the whole water column, minimal in surface layers and maximal in bottom layers. Within several weeks, DO content in near-bottom water over local hollows where OM is located may drop down for 80–90% of initial values or even disappear altogether (Figure 2a).

The main reason for such a case is the different rate of bacterial DO consumption over local deepenings and declined bottom. Here, bacteria mineralize not only OM stored in the upper layer of bottom sediment but also in the near-bottom waters. Their activity depends on the water temperature, which is higher there compared to shallower waters and actively grows during the second stage due to heat transferred from lake sediment. Over the declined bottom, the vertical DO profile looks different, that is, a drastic decrease can be observed only in the very vicinity of lake sediment (Figure 2b). This is a result of OM absence in the near-bottom waters of such areas.

The third stage starts when the vertical temperature profile becomes nearly linear and quasi-stationary, that is, heat flux from sediments is balanced by heat loss from water to ice. By then, the near-bottom DO deficit is formed (the case for some shallow oligotrophic and mesotrophic lakes). In lakes where OM amount is very high (eutrophic and hypereutrophic lakes), the deficit transforms into depletion with eventual appearance of the dead zone, which may, if a lake depth is small, spread out through the whole water column, leading to the fish kill.

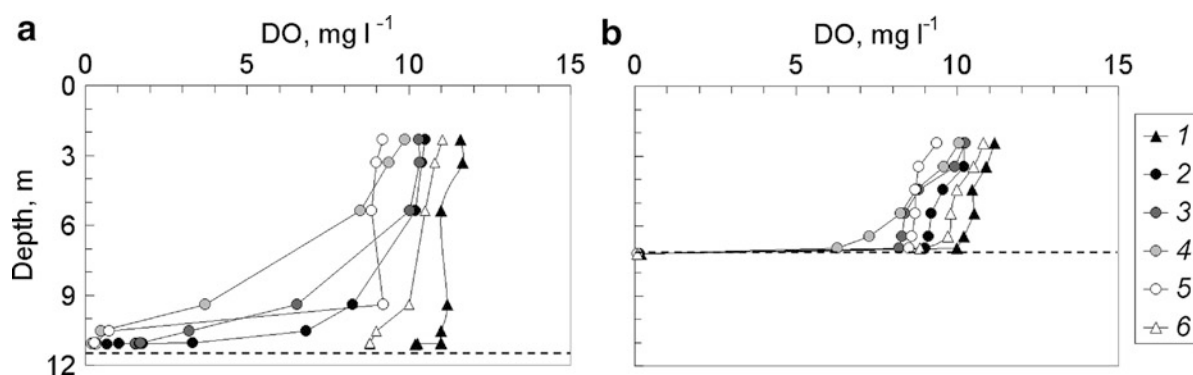
During the third stage, DO content decreases not only in the lower part of a water column but also in the middle layers. This occurs due to the molecular DO flux directed from relatively “DO-rich” layers toward a lake bottom where DO content is much lesser. The anaerobic zone, if any, stops to grow as DO consumption on its upper

boundary is compensated by the molecular DO flux. Such situation usually lasts until late winter. By then, the snow cover disappears, and solar radiation starts to penetrate through ice into water, initiating the under-ice convection.

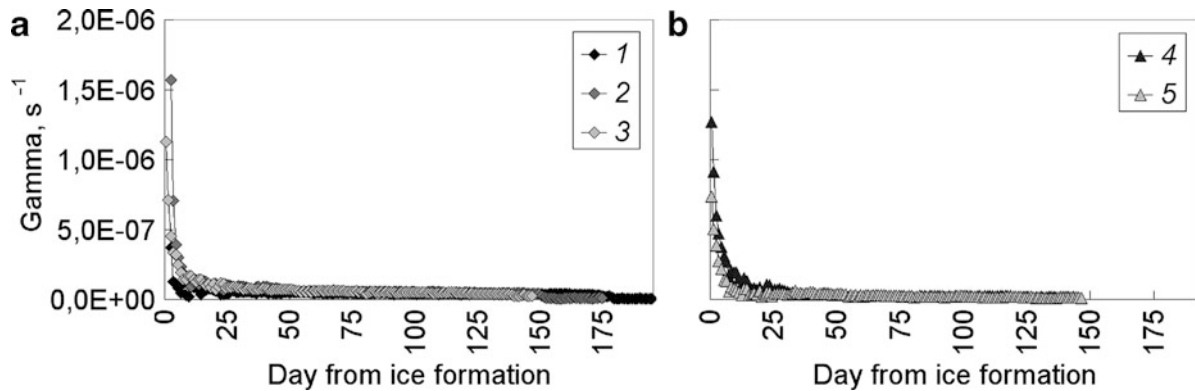
To this very moment, the last – fourth – stage starts. As lake productivity was suppressed during winter, water transparency is high, and solar radiation penetrates deep into the water column, increasing its temperature. As upper layers are heated stronger, it leads to the development of convective instability and eventual mixing. Within this convectively mixed layer, DO content is quasi-uniform (Figure 2). If a lake is shallow enough, convection may reach its bottom. Because of absence of DO external sources, absolute values of DO content, being distributed within a larger volume, get smaller. The fourth stage is the shortest and lasts for a couple of weeks. Once the ice cover disappears, aeration of the water column due to interaction with atmosphere and wind mixing takes place (Figure 2, profiles 6). DO deficit/depletion and dead zones vanish. During the open-water period, it may appear again, but this is a different story.

Summary

Because of its numerous negative consequences, DO depletion may endanger the ecosystems of shallow lakes. Therefore, the development of forecasting methods is of vital importance. Among others, numerical modeling of seasonal DO dynamics in water bodies looks very promising. During the last decades, some positive experience has been collected (Bell et al., 2005; Fang and Stefan, 1997; 2009; Golosov et al., 2007). One of the bottlenecks for such models is poor knowledge on empirical (not universal) parameters included into the models. Primarily, it concerns the bacterial DO consumption rate. To resolve a problem, the targeted field observations are needed. An example of observational data use is given below. Data itself are records of DO content at different depths of a water column in a shallow mesotrophic lake registered regularly



Dissolved Oxygen in Ice-Covered Lakes, Figure 2 Vertical DO profiles in a shallow ice-covered lake: 1 stands for the last days before ice cover formation, 2 for early winter, 3 for mid-winter, 4 before under-ice convection, 5 after convection, and 6 after ice cover disappearance; (a) over local deepenings, (b) over slopes. Dashed line marks the water–sediment interface. Based on unpublished data of NWPI.



Dissolved Oxygen in Ice-Covered Lakes, Figure 3 Temporal dynamics of the DO consumption rate $\gamma = \ln(C/C_0)/t$, see the text: 1–3 stands for three winters over local deepenings, 4–5 for slope locations; (a) local deepenings, (b) slope. Based on unpublished data of NWPL.

(1 min apart) throughout all winter, which are used to calculate depth-average values of DO concentrations.

Typically, the development of any non-conservative substance C in time can be described as,

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = (D_t + D_m) \frac{\partial^2 C}{\partial z^2} \pm S. \quad (2)$$

Here, u , v , and w are current vector components along corresponding axes; D_t and D_m stand for turbulent and molecular diffusivities, respectively; $S = \gamma C$ is a term describing sources and/or sinks of non-conservative substance; γ is the substance consumption rate. Scaling analysis (see, e.g., Terzhevik et al., 2009) allows to simplify Equation 2 as,

$$\frac{\partial C}{\partial t} = -\gamma C, \quad (3)$$

with a corresponding analytical solution

$$C = C_0 e^{-\gamma t}. \quad (3a)$$

Here, C_0 is the initial value of substance C , in our case prescribed as DO concentration at the moment of ice cover formation. The DO consumption rate γ can be estimated as an inverse problem of Equation 3a, that is, $\gamma = -\ln(C/C_0)/t$, given known values of the initial and final DO concentrations for the period t , in seconds.

Figure 3 demonstrates the use of observational data to evaluate temporal dynamics of the DO consumption rate γ in a shallow ice-covered lake. As one can see, the most drastic consumption occurs in first weeks of the ice-covered period. For the rest of the observational period, the consumption rate can be considered as quasi-constant, and this value can be used for estimates of the seasonal change of DO content.

Of course, this text cannot be considered as a full description of the winter DO regime in shallow ice-covered lakes. The authors have briefly presented current

knowledge and some results of their 10-year research on the problem considered. It is quite plausible that the actual cause of the DO dynamics in some ice-covered lakes may deviate to some extent from the general picture, which presents only the main mechanisms that govern the process.

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DOUBLE-DIFFUSIVE CONVECTION IN LAKES

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Definition

Double-diffusive convection in lakes is a pattern formation in density stratified lakes, which results from largely different diffusivities of dissolved substances and heat.

Double-diffusive convection has been investigated in laboratory experiments and has been documented in tropical lakes (Lake Kivu: Newman, 1976, Lake Nyos: Schmid et al., 2004), but also in meromictic lakes of the temperate climate zone (von Rohden et al., 2010).

Introduction

When two physical quantities of different diffusivities contribute to density, double-diffusive convection can occur. Such features are visible if heat is one of the factors, as the diffusivity of heat is two orders of magnitude higher than of dissolved substances. However, from lab experiments, it is known that double-diffusive features can also occur at an interface of solutions of different substances (e.g., salt and sugar). For a general overview of double-diffusive effects, see the publication by Turner (1995), with a focus on limnological implications see the chapter by Imboden and Wüest (1995).

Of special interest is the case when one of the components keeps the overall stratification stable, while the other component delivers a density contribution, which weakens the density gradient. The stability ratio of the stabilizing effect over the destabilizing effect R_ρ classifies this system. For overall stable configuration, $R_\rho > 1$. Double-diffusive convection is in particular visible if the destabilizing component is of the same order of magnitude as the stabilizing effect, i.e., $1 < R_\rho < D_T/D_S$, the ratio

of the diffusivities of the respective quantities of heat (or temperature T) and dissolved substances (salinity S) with increasing intensity when approaching unity. Two cases can be distinguished (Figure 1).

Considering a two-layer system, with the stabilizing component diffusing faster than the smaller, opposing effect component, e.g., a cold but fresh water layer overlain by a hot water layer of higher salinity (so-called finger regime). Hence

$$R_{\rho(\text{finger})} = \frac{\alpha dT/dz}{\beta dS/dz}$$

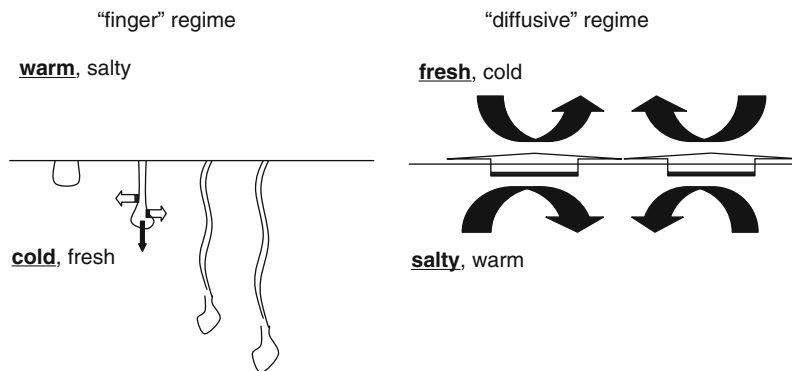
where $\alpha dT/dz$ is the density gradient along the vertical axis z due to temperature T , while $\beta dS/dz$ represents the density gradient due to dissolved salt. $\alpha = \frac{1}{\rho} \frac{\partial \rho}{\partial T} = -\frac{1}{\rho} \frac{\partial \rho}{\partial T}$ is the thermal expansion coefficient, and $\beta = \frac{1}{\rho} \frac{\partial \rho}{\partial S}$ is the coefficient of haline contraction.

A small density disturbance of salt water at the interface proceeds little into the lower layer and hence is exposed to stronger heat exchange than at its original position. Due to the higher diffusivity of heat compared to salt, density is continuously gained by the droplet, and it proceeds into the lower layer, leaving a fine line of increased salinity in its wake. Many droplets next to each other explain the term “finger” regime.

The opposite case is called the “diffusive regime.” Salt water lies under a fresh water layer of lower temperature. The density ratio now is defined as

$$R_{\rho(\text{diffusive})} = \frac{\beta dS/dz}{\alpha dT/dz}.$$

Heat is crossing the interface, and each layer is convectively driven from this interface. In this configuration, there is no limit of the vertical convective motion. An interesting case appears when we have to deal with a continuous stratification. Then the convection is



Double-Diffusive Convection in Lakes, Figure 1 Double-diffusive convection at an interface between two layers of different properties. Left panel: finger regime, right panel: diffusive regime. Water motion is shown by solid arrows, while heat diffusion is displayed with open arrows.

confined to a certain layer thickness, where the background stratification does not permit a further ascent. A series of convection cells appears on top of each other, leaving a staircase of steps in the profiles of conductivity (and temperature, see Figure 2).

Such steps can develop from originally smooth profiles, e.g., by a seasonal temperature forcing (von Rohden et al., 2010). The staircase is the consequence of a pattern formation. A length scale for the steps can be derived (e.g., Kelley, 2003), which coincides with observations reasonably well (see Schmid et al., 2004); even thin layers extend over hundreds of meters horizontally (von Rohden et al., 2010). Double diffusion forces a highly enhanced vertical transport of heat and substances and hence has environmental implications.

However, double-diffusive convection does not only occur in the monimolimnia of meromictic lakes, but it is also present when intrusions of different salt concentration/composition and temperature proceed into a stratified lake. Propagation speed and vertical spreading can be controlled by double-diffusive effects. In other cases, biogeochemical transformations have been shown to enhance double-diffusive effects (Boehrer et al., 2009). Even the layered sedimentation of different

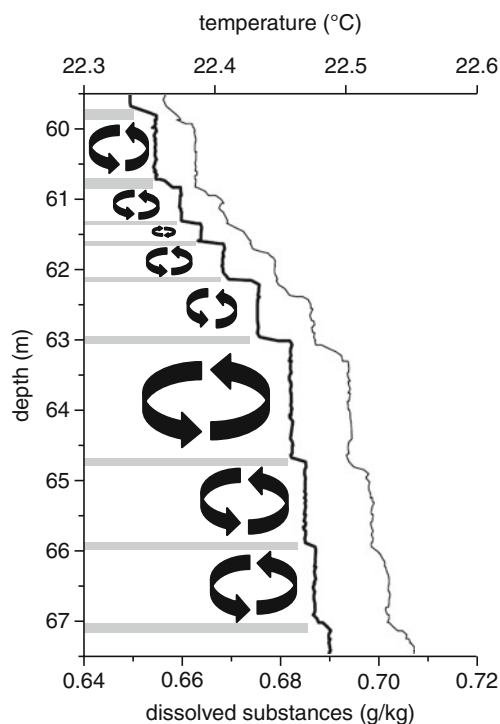
minerals has been brought related to double diffusion. An overview of possible implications of double diffusion can be found in Turner's (1995) text and the monograph by Brandt and Fernando (1995).

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Cross-references

[Baikal, Lake](#)
[Mixing in Lakes](#)
[Stratification in Lakes](#)
[Thermobaric Stratification of Very Deep Lakes](#)



Double-Diffusive Convection in Lakes, Figure 2 Double-diffusive convection cells creating a staircase of electrical conductivity in a profile of Lake Nyos (Modified from a display in Schmid et al., 2004). Convection cells of several decimeters thickness alternate with layers of no convection (in gray), where heat is transported diffusively.

DROUGHTS AND WATER MANAGEMENT IN ENGLAND AND WALES: WITH PARTICULAR REFERENCE TO RESERVOIRS AND LAKES

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Introduction

Reservoirs and lakes are major sources of water supply, power generation, and ecological diversity; they also have considerable amenity value and commonly provide extensive recreational opportunities. In most countries, they constitute a primary component in water resources management systems which help bolster resilience to periods of drought. During dry episodes especially, careful stewardship and management of water bodies is essential to ensure that, with temperatures and water demand increasing, drought impacts on both human and wildlife populations are moderated. Here, the impact of droughts over the last 50 years on reservoirs and lakes in England

and Wales is reviewed in the context of refinements in water management strategies and the challenges posed by global warming.

Background

England and Wales has a temperate climate with rainfall well distributed throughout the year but with a tendency towards an autumn and early winter maximum. With a 1971–2000 mean annual rainfall of 1,112 mm, it is one of the wettest countries in Europe but this disguises very wide spatial variations. In the driest parts of Southeast England, the annual average falls below 500 mm while annual totals can be an order of magnitude higher in the hills of Northwest England. Average annual evaporation losses span a relatively narrow range – typically 350–550 mm – with around 75% of the total normally occurring during the summer half-year (April–September). Correspondingly, the bulk of the replenishment to reservoirs occurs during the winter half-year. During the late spring, summer, and early autumn, water demand normally exceeds replenishment and reservoir stocks decline.

There are estimated to be around 200,000 ha of permanent lakes and nearly half a million small ponds which constitute an integral part of the UK landscape and, together, represent around 20% of the surface area of the country (National Ecosystem Assessment, 2011). Many of the larger natural lakes are used for water resources purposes, and they form a significant minority of the more 400 reservoirs in England and Wales. Most large reservoirs are components in complex regional water supply networks (see below) and many are multifunctional: moderating flood risk, generating hydropower, and providing recreational opportunities.

In the wet, impermeable uplands of the West and North of the country, most reservoirs are gravity-fed while off-line pumped storage impoundments provide a major component of the overall water storage in the drier and flatter East and South of the country where the terrain, and permeable nature of the bedrock, affords much fewer opportunities for reservoir construction.

In broad terms, the primary water management challenge in England and Wales is that population, commercial activity, and intensive agriculture – which generate the highest water demand – are concentrated in the driest parts of the country where, on average, annual rainfall totals only modestly exceed evaporation losses. Correspondingly, innovative and flexible water management strategies are required to maintain water supplies – particularly during extended periods of rainfall deficiency.

What is a drought?

Droughts are a natural component of climatic variability. The concept of a drought is generally well understood but translating that understanding into a robust quantitative mechanism for indexing drought extent and severity remains a considerable challenge. This reflects the difficulties in quantifying a phenomenon which varies in its causation, extent, duration, intensity, and, particularly, its

range of impacts. Useful distinctions can however be drawn between meteorological droughts defined essentially on the basis of rainfall deficiency; hydrological droughts – where accumulated shortfalls in runoff and aquifer recharge are of primary importance; and agricultural droughts – where the availability of soil water through the growing season is the critical factor.

In relation to water management, hydrological droughts – and the attendant paucity of runoff and aquifer recharge – are of most direct significance, along with the scale of the water demand that the available resources have to service. In addition, the ability of reservoirs and lakes (and downstream rivers) to sustain a healthy and diverse aquatic environment during drought episodes has assumed an increasing significance over the last 20 years.

Drought in England and Wales does not constitute the very real threat to lives and livelihoods that it is throughout much of the world but reconciling the, often competing, demands for water while maintaining a healthy aquatic environment presents considerable scientific, engineering, and organizational challenges.

Droughts impact on lakes and reservoirs as a consequence of reduced inflows, reduced surface rainfall, and increased surface water evaporation losses; high water temperatures can also contribute to water quality problems. The size of reservoirs, as well as the water demands on them, is reflected in the duration of drought to which they are most vulnerable. A combination of modest rainfall and high evaporative demands means that summer droughts often impact severely on agricultural reservoirs and small water bodies. Open-water evaporation losses are influenced by temperatures, windspeed, sunshine hours, and humidity and can appreciably exceed potential evaporation losses; losses may exceed 500 mm during an arid spring and summer. Evaporation losses on this scale during periods of rainfall deficiency can be sufficient to dry up many ponds and shallow lakes. They can also impact appreciably on large reservoirs stocks – accounting for up to 15% of capacity in some lowland impoundments. However, most large reservoirs (and regional groups of reservoirs that are operated as a single resource) can normally withstand even exceptionally dry summers and, generally, are most vulnerable to winter droughts especially when the rainfall deficiencies extend over two, or more, successive years (see below).

Droughts and their impact on water resources

The UK's vulnerability to extended periods of rainfall deficiency was well demonstrated during the late 1950s and early 1960s. An intense drought in 1959 affected most of the country and was followed, in 1962–1965, by three of the driest winters in the last 100 years. These episodes, together with projections of a doubling in water demand over the latter half of the twentieth century, stimulated the creation of the Water Resources Board – charged with developing a strategic blueprint for water resources development in England and Wales. This heralded a period of increased reservoir construction and the

development of more sophisticated water resources management strategies – incorporating increasing usage of regional water transfers, river regulation, conjunctive use of surface and groundwater resources, and, generally, more integrated regional water management.

The resilience of the UK's water resources infrastructure was severely tested during the extremely intense drought of 1975/76 (Rodda and Marsh, 2011). The period May 1975–August 1976 was the driest for any 16-month sequence in a rainfall series for England and Wales that extends back to 1767 (Wigley et al., 1984). Through the spring and exceptionally hot summer of 1976, overall reservoir replenishment rates were the lowest recorded in the twentieth century. The drought had widespread environmental and agricultural impacts (Doornkamp et al., 1980; Rodda and Marsh, 2011) and water resources were exceptionally stressed during the late summer and early autumn. Reservoir stocks fell to only around 10% of capacity in a few parts of Southwest England, and hose-pipe bans extended across most of the country by July. As resources dwindled, additional water conservation measures were included in the 1976 Drought Bill which was fast-tracked through Parliament. In the event however only local, and very temporary, recourse to rota cuts or standpipes for public water supplies were needed (and

these were due largely to the limited interconnectivity of local water supply networks) before exceptional autumn rainfall brought an unusually rapid termination to the drought.

A short but intense April–August drought in 1984 impacted primarily on Northern and Western Britain (Marsh and Lees, 1985). Steep declines in reservoir stocks through the spring and summer, exacerbated by open-water evaporation rates of >5 mm per day, resulted in very depressed late summer reservoir levels (see Plate 1). Water conservation measures were widely implemented before the drought conditions were alleviated during a notably wet autumn. Generally, the 1980s was a relatively wet decade but the very dry winter of 1988/89 generated significant public and political concern about the UK's vulnerability to drought. One consequence was the initiation of a National Hydrological Monitoring Programme (Anon, 2011) to routinely collate and analyze a range of hydrometeorological variables, and document both hydrological variability and water resources status. Included in the program was the monitoring of reservoir stocks for a representative network of major reservoirs throughout the country. The aggregated stocks for England and Wales provide a convincing index of the overall impact of drought episodes on water resources (see Figure 1).

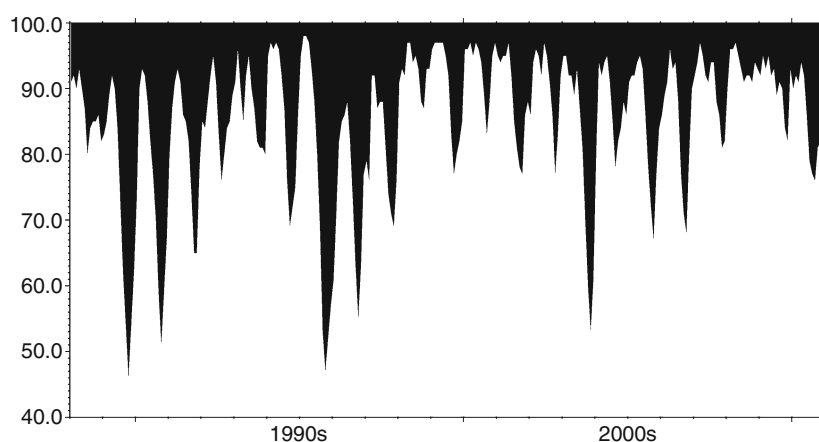


Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes, Plate 1 Haweswater reservoir in August 1984 (Photo credit: Jackie Carr).

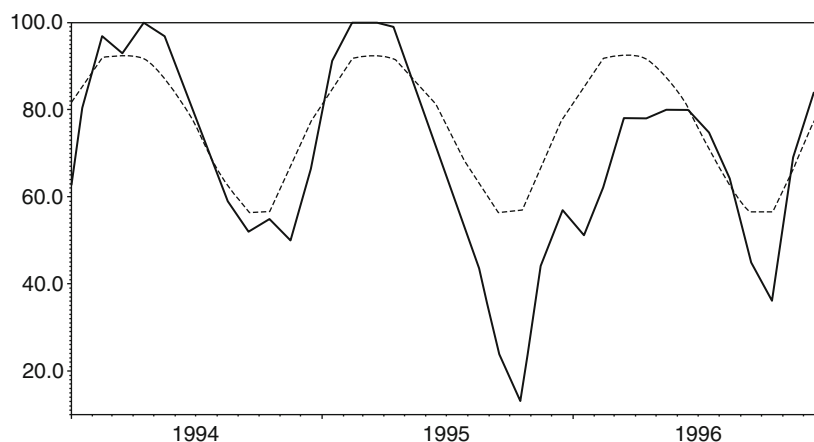
The 1990s were characterized by sustained wet and dry episodes and two protracted droughts which stressed both reservoir stocks and groundwater resources (Marsh et al., 1994; Marsh, 1998). Runoff over the September 1990–August 1992 period was less than 50% of average in parts of Eastern England and many reservoirs failed to refill over the 1991/92 winter. In the ensuing spring, the water resources outlook was fragile throughout much of Western Europe (Marsh, et al., 1994). Fortunately, the summer and autumn of 1992 were notably wet and drought stress was largely eliminated through the winter of 1992/93.

The winter of 1994/95 was also wet and water resources were very healthy entering the spring. However, from the beginning of April, the driest 5-month sequence on record for England and Wales resulted in an exceptionally steep

decline in reservoir stocks. A heat wave in August increased water demand and overall reservoir stocks fell below 50% of average by the end of the summer. In Northwest England, the combined stocks for a group of reservoirs servicing major conurbations to the south fell below 15% of capacity (Figure 2). This serves to emphasize that, in circumstances where demand is high and rainfall extremely low, the critical period for a major resource can be relatively short. The dry and hot summer also resulted in reduced oxygen levels and widespread water quality problems in lakes and reservoirs. Entering the autumn, almost 20 million people were affected by hose-pipe bans and, though varying substantially in intensity, drought conditions continued through to 1997 by which time, groundwater levels in the major aquifers were very



Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes, Figure 1 Overall stocks (% of capacity) for a representative network of large reservoirs in England and Wales.



Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes, Figure 2 1994–1996 reservoir stocks (% of capacity) for a group of reservoirs in Northwest England (the broken trace indicates mean monthly stocks).

depressed. This restricted the options available to water managers to relieve pressure on surface water storages.

The 1995–1997 drought's termination heralded the wettest 5-year sequence on record for England and Wales, but early in 2003, a further drought episode was initiated, and became severe through the exceptionally warm summer. The drought's impact was extensive and diverse, affecting much of Western and Southern Europe. By the autumn, large rainfall deficiencies extended across all regions of the country (Marsh, 2004) but the drought was most severe in Southeast England where record temperatures contributed to exceptional rates of open-water evaporation. Many ponds dried up, wetlands contracted, and, with water and oxygen levels low, many fish rescues were required. Nonetheless, despite the second driest February–October on record, overall stocks in the reservoirs supplying London's water needs remained above 50% of capacity apart from a brief interlude during September and no restrictions on water usage (other than spray irrigation) were required. This demonstrates a considerable degree of resilience to within-year rainfall deficiencies when the wetness of the preceding winter ensures that reservoir stocks are near to capacity and groundwater (a significant component of water supply in Southeast England) levels close to seasonal maxima entering the spring.

The particular importance of winter rainfall was again underlined during the protracted drought of 2004–2006 when, across Southern Britain, November–April rainfall totals were depressed over successive years. Correspondingly, a substantial proportion of reservoirs failed to refill before the spring recessions became established in 2005 and 2006 (see Figure 3). By the summer of 2006, with groundwater levels also notably low, hosepipe restrictions applied to 13 million consumers and many ponds (see Plate 2) and groundwater-fed wetlands were greatly diminished in size.

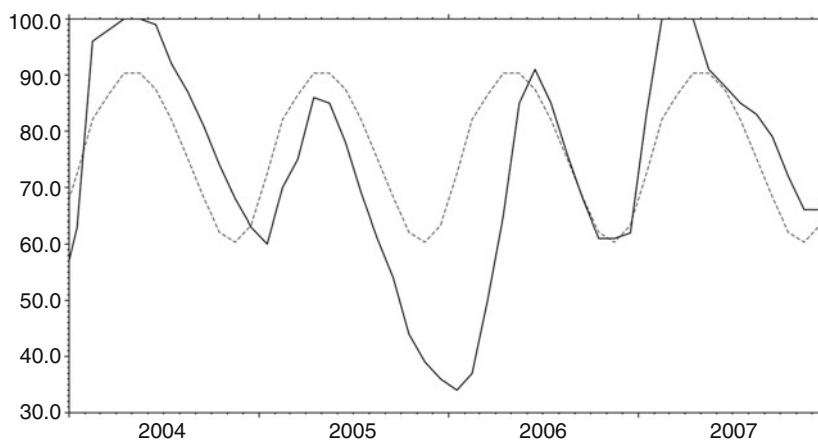
Water resources and drought management in England and Wales

Water management measures to counteract drought fall broadly into two categories: strategic and tactical – both attempting to influence the balance between water demand and available resources.

The former group embraces the establishment of appropriate legislative and regulatory frameworks augmented by suitable planning controls (e.g., to moderate development in water-stressed areas). In England and Wales, the Department for Environment, Food and Rural Affairs (Defra) and the Welsh Government are responsible for water resources policy while management is principally the responsibility of the Environment Agency which works with the water supply companies to regulate the supply of water and protect the environment.

The statutory framework establishes a long time horizon within which to address the threat of drought. All water supply companies are required to prepare drought plans outlining how they propose to manage water resources (including demand) in the future without detriment to the environment (Environment Agency, 2011). Also falling into the strategic category are: improvements in drought forecasting capabilities and water exploitation strategies, medium-term measures to moderate demand (e.g., the promotion of more efficient domestic, industrial, commercial and agricultural water use; bearing down on mains leakage rates, increasing the proportion of domestic metering, and introducing smart water use tariffs which reward moderate usage).

The tactical category includes an escalating series of contingency measures to be introduced as drought conditions intensify (Walker, 1998). They are directed toward conserving stocks in circumstances where there is likely to be great uncertainty regarding when a drought episode will end. The measures address mechanisms for supplementing



Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes,
Figure 3 2004–2007 reservoir stocks (% of capacity) for Bewl Water in Southeast England (the dashed trace indicates mean monthly stocks).



Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes, Plate 2 A depleted pond during the 2004–2006 drought in Southern England (Photo credit: Terry Marsh).

available water supplies, constraining demand, and engaging with stakeholders to agree to an equitable partitioning of limited resources between often competing needs, while ensuring, so far as is practicable, that the environment and aquatic habitats are protected during periods of drought. Typically these involve media campaigns to moderate demand, and a temporary relaxation of statutory conditions on water abstractions, for example to reduce compensation releases from reservoirs. Where an exceptional shortage of rain can be demonstrated, water companies can apply for Drought Permits or Drought Orders (Department for Environment, Food and Rural Affairs, 2011). These are legal mechanisms which allow greater flexibility in managing water resources. A permit may allow additional water to be abstracted from a specified source or modify the conditions in an existing abstraction license. Drought Orders go further and can allow water companies to limit particular uses of water (e.g., bans on the use of hosepipes). In extreme drought conditions, Emergency Drought Orders allow particular categories of water use to be prohibited and the use of standpipes or water tanks to restrict public demand.

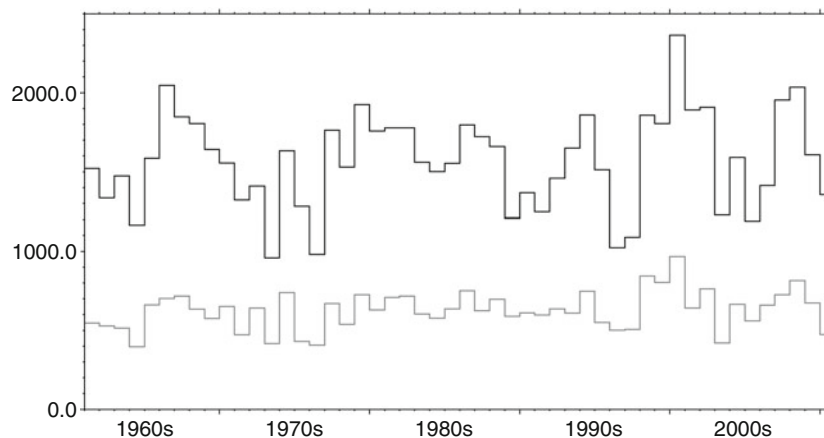
Operationally, much can be achieved by temporarily switching supply sources (e.g., by preferentially abstracting from groundwater or river abstractions to alleviate pressure on depleted reservoir stocks, increasing regional, or local, transfers of water to augment supplies in drought afflicted areas) or by reducing main pressures to limit leakage losses.

The robust statutory framework, together with increased regional and local inter-linkages between supply sources and scientifically based improvements in water

and environmental management, has helped to ensure that the deployment of standpipes and water tanks (in response to drought conditions) has not been needed since the end of the 1976 drought.

Climate change

The cluster of drought episodes over the 1990–2010 period heightened concern among the public and policy-makers that runoff variability and drought frequency may increase in a warmer world. In a period of actual, or anticipated, climatic change the management of water resources and the protection of the aquatic environment during periods of drought stress, present considerable challenges. Historically, water management strategies in the UK, as elsewhere, have been predicated on an assumption that rainfall and runoff variability occurred around a relatively stable long-term mean. This is an inadequate policy foundation in the face of anthropogenic climate change. Most climate change scenarios indicate that a warmer UK will also have higher potential evaporation demands, wetter winters, and drier summers (UKCP09, 2009). However, the uncertainty bands are wide, particularly in relation to how increasing temperatures will impact on rates of runoff and recharge – the critical factors in relation to water resources stress – across the wide range of catchment types encountered in England and Wales. It is essential therefore to maintain and improve observational monitoring programs to identify and quantify trends and, over time, to establish a fuller reconciliation between climate change scenarios and observational evidence; this is a necessary prerequisite for future policy development.



Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes, Figure 4 Estimated annual mean outflows ($\text{m}^3 \text{s}^{-1}$) for England and Wales (gray trace), 1961–2010.

Temperatures in England and Wales have increased by 1.2°C over the last 50 years, a very rapid rise in a historical context. This impacts directly on open-water evaporation rates and has implications for the frequency with which shallow water bodies (village ponds for example) dry up. Of more direct water resources interest are changes in rainfall, runoff, and aquifer recharge. Any significant reductions would be of concern especially across many southern areas where available resources are already heavily committed. Changes in the seasonality of rainfall could also have wide implications, particularly for smaller reservoirs. A combination of lower spring rainfall and increased evaporation rates could lead to steeper declines in reservoir stocks with potentially increased water supply stress during the late summer and autumn – before the seasonal recovery in runoff rates allows stocks to be replenished.

In contrast to temperature, observational evidence of recent trends in rainfall and runoff is much less compelling. There is no trend in annual mean precipitation totals over the 236-year national rainfall series (Jenkins et al., 2008) and, while some modest regional tendencies in runoff have been identified over time spans of 40 or more years (Hannaford and Harvey, 2010; Hannaford and Marsh, 2006), analyses of total outflows at the national scale suggest a long-term stability in runoff rates, albeit with substantial temporal variability. Figure 4 shows annual mean outflows for England and Wales based on fixed networks of gauging stations measuring outflows from major river basins. The variability between, and within, the five decades is considerable but there is no indication of any sustained decline in runoff. Indeed, the possibility that a tendency for a greater proportion of the overall rainfall to occur in the winter half year (October–March) may be reflected in the slight tendency for runoff to increase over the post-1960 period.

Indexing the direction, pace, and magnitude of any temperature-driven changes in runoff is the key to effective drought management in the future but any such changes

will be superimposed on natural climatic variability. Rainfall series extending back almost 250 years in England and Wales confirm that substantial seasonal changes have occurred. Most notably, winters in the nineteenth century tended to be drier than summers and clusters of dry winters were common. Over the 1890–1910 period, some southern regions registered only two or three wet winters and any modern repetition of this “Long Drought” (Marsh et al., 2007) would represent a real water resources challenge given contemporary water demands and environmental imperatives. A greater understanding of the mechanisms that influence multi-year and multi-decadal variations in drought frequency would allow drought mitigation strategies to be honed more effectively – adapting to periods when the probability of sustained rainfall deficiencies is increased.

Summary

Advances in the exploitation and management of water resources in England and Wales over the last 50 years have provided a substantial measure of resilience to all but the most extreme drought conditions. As yet there is little evidence to indicate that runoff at the national scale has decreased due to global warming and a modest tendency toward wetter winters would, if continued, have significant water resources benefits. However, the impact of both climate change and climate variability needs to be considered alongside projections of increases in population, domestic and agricultural water demand, and the priority afforded to the protection of the aquatic environment. This implies the need for a continuing review of drought mitigation strategies informed by rigorous methodologies to identify and quantify observational changes in runoff patterns across the country.

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[Reservoirs in Great Britain](#)

E

ECOLOGICAL THREAT TO LAKES AND RESERVOIRS

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Definition

Lakes and reservoirs hold about 90% of the world's fresh surface water. According to the discussions at the 9th International Conference on the Conservation and Management of Lakes held in Shiga, Japan, in 2001, warning was given of some one billion people being at risk from overuse, water withdrawals, and pollution of these water bodies. Similar warnings were given at the 3rd World Water Forum at the Kyoto Conference in 2003.

The principal threats worldwide appear to be:

- Accelerated eutrophication, which affects 54% of the lakes in the Asia-Pacific region, 53% in Europe, 28% of those in North America, and 41% of those in South America
- Chemical pollution, which is the second most commonly cited threat to lakes
- Alien plant and animal species, either introduced into lake environments in the ballast water of ships, as part of the aquarium trade, from small boats traveling between lakes, or in bait and by escaping from aquaculture, with some intentionally introduced to boost fishery production or to control another exotic species
- Acidification, which is a serious problem in most of central and northern Europe, the northeastern United States and southeastern Canada, Australia, New Zealand, Japan, and China, with many lakes in Scandinavia and the affected regions of North America becoming so acidic in the past few decades that they can no longer sustain the diverse forms of life originally found there

- Water withdrawals, which have risen to 3,800 cubic kilometers per year, one study estimating a sixfold increase in water withdrawals from lakes and rivers between 1990 and 1995

In industrialized countries, shallow lakes are the most endangered, especially those situated in areas of intensive agriculture or which have been depleted for drinking water and industrial uses. Those that are most at risk include the US' second largest lake, Lake Okeechobee, which has an average depth of just 10 ft (3 m); Arre Lake in Denmark; Hungary's Lake Balaton; the Aral Sea between Kazakhstan and Uzbekistan, which has dropped in area from the world's fourth largest lake to the eighth largest; and the world's deepest lake, Russia's Lake Baikal, containing about one fifth of the world's fresh surface water, facing pollution from industrial plants.

In the developing world, some of the most threatened lakes include Africa's largest, Lake Victoria and Lake Chad which has been reduced to one twentieth its size in four decades, and Taihu Lake in China because of severe pollution.

Once a lake becomes degraded, it takes a considerable time and a great deal of effort to restore it to health, and, as a consequence, successful restorations are rare, particularly in the case of large lakes. One success story is Lake Washington near the US city of Seattle, which was highly eutrophic until the 1970s, but was restored by installing a wastewater treatment system and diverting the treated effluent out of the lake's watershed. Managing lakes is difficult, not only entailing resolving important technological, financial, and institutional issues but also requiring support from industry and the public as well as government. A participatory, watershed-based approach is much more difficult to achieve for lakes in developing countries, where political instability and the lack of financial resources may be more common.

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[Climate Change Effects on Lakes](#)
[Climate Change: Factors Causing Variation or Change in the Climate](#)
[Large Dams and Environment](#)
[Water Exchange Between Littoral Zone and Open Lake Water](#)
[World Lake Vision](#)

ENGLISH LAKES

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Introduction

The Lake District of England is not only famous for being one of England's prime tourist resorts but also its lakes being the subject of significant scientific study over the past 100 years. A considerable input to this scientific study has been undertaken since 1931 by the Freshwater Biological Association (FBA) and the Institute of Freshwater Ecology (IFE).

There are some 88 lakes and tarns (small lakes) in the group of lakes in the district of north east England.

It is interesting to note that only one of these lakes is known as a "lake" the one being Bassenthwaite Lake, all the others being tarns as in Blelham Tarn, or "mere" as in Windermere or with "water" in the name as in Ullswater.

Geology

The geology of the Lake District is complex with Skiddaw Slsate and Borrowdale Volcanic rocks formed some 500 million years ago. A system of radiating U shaped valleys formed by glaciation some 15,000 years ago subsequently filled with the lakes we see today. On three sides there is a rim of carboniferous limestone.

The area of the Lake District is about 2,300 km² with a width from east to west of 55 km.

Ecology

The physical, chemical, and biological characteristics of the 15 most important lakes are given in [Tables 1–3](#) from J.F.Talling ed. published with permission of the Director of the Freshwater Biological Association, Windermere, Cumbria, UK.

Retention time

The mean retention time of a lake is an important characteristic especially if water has to be extracted from the lake. Mean retention time, RT, is

$$RT = V \div I$$

where V is the lake volume and I is inflow rate, the latter being the amount of rainfall plus streamflow. For an approximate solution to the equation for the Lake District,

English Lakes, Table 1 The Cumbrin lake series: geographical and physical features of major lakes arranged in order of increasing productivity, estimated from mean chlorophyll-*a* concentrations in 1991. Secchi disc transparency is given for the summers of 1952 and 1991. Depth of euphotic zone is for June–August 1952. Data IFE 1991 (IFE Lakes Tour in 1991)

Lake	Alt (m)	Area (km ²)	Max depth (m)	Mean depth (m)	Volume (10 ⁶ m ³)	Secchi transp. (m)		Euphotic zone (m) 1952	Area of drainage basin (km ²)
						1952	1991		
Wastwater	61	2.91	76	39.7	115.6	–	13.0	38.3	48.5
Ennerdale Water	112	3.00	42	17.8	53.2	9.2	10.0	35.5	44.1
Thrimere (R)	179	3.27	46	16.1	52.6	–	8.4	14.6	29.3
Buttermere	101	0.94	29	16.6	15.2	13.8	16.0	>Max. depth	16.9
Crummock water	98	2.52	44	26.7	66.4	12.0	9.0	24.2	43.6
Haweswater (R)	240	3.91	57	23.4	76.6	–	5.3	16.6	26.6
Coniston water	44	4.91	56	24.1	113.3	–	5.0	14.6	60.7
Derwentwater	75	5.35	22	5.5	29.0	–	4.5	14.9	82.7
Grasmere	62	0.64	21.5	7.7	5.0	–	3.0	9.7	27.9
Windermere NB	39	8.05	64	25.1	201.8	5.0	4.5	14.6	–
Loweswater	121	0.64	16	8.4	5.4	5.2	3.5	8.5	8.9
Bassenthwaite Lake	69	5.28	19	5.3	27.9	–	2.5	6.2	237.9
Ullswater	145	8.94	62.5	25.3	223.0	5.8	6.5	13.3	145.5
Windermere SB	39	6.72	42	16.8	112.7	–	3.1	13.3	–
Windermere (TL)	39	14.76	64	21.3	314.5	–	–	–	230.5
Blelham Tarn	42	0.10	14.5	6.8	0.7	–	1.6	8.9	4.3
Esthwaite water	65	1.00	15.5	6.4	6.4	3.0	1.3	9.7	17.1

Alt = altitude above mean sea level; R = reservoir; TL = Windermere total lake, NB = North Basin, SB = South Basin

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English Lakes, Table 2 The Cumbrian lake series: major ion concentrations (microequivalents per liter) and pH, given as mean values within the period 1974–1978. Data IFE 1991

Lake	Ca ²⁺	Mg ²⁺	Na ²⁺	K ⁺	Alk	Cl ⁻	SO ₄ ²⁻	pH
Wastwater	114	62	172	10	50	186	101	6.7
Ennerdale water	100	72	187	10	42	208	102	6.5
Thirlmere (R)	148	42	159	8	50	175	112	6.5
Buttermere	118	51	160	7	48	192	91	6.2
Crummock water	126	73	181	9	43	215	106	6.6
Haweswater (R)	249	78	148	12	175	155	142	6.8
Coinston water	318	91	220	15	178	259	183	6.9
Derwentwater	236	55	220	9	98	298	109	6.7
Grasmere	237	56	184	10	141	191	138	6.8
Windermere NB	314	81	202	14	204	222	157	7.0
Loweswater	291	130	266	21	175	321	171	6.9
Bassenthwaite Lake	310	111	251	18	189	309	147	6.9
Ullswater	293	87	172	12	231	178	136	7.0
Windermere SB	355	92	219	17	236	242	171	7.1
Blelham Tarn	542	136	222	26	403	248	242	7.0
Esthwaite water	526	123	249	25	386	282	231	7.1

Alk = alkalinity, largely HCO₃. R. NB and SB as in Table 1

Table published with permission of the Director FBA

English Lakes, Table 3 The Cumbrian lake series: additional chemical features of biological significance. Concentrations are in micrograms per liter, Oxygen depletion in August (consistent +, variable var) is at near-bottom depths. (Data from IFE Lakes Tour in 1991; further, the last column shows overall mean values for chlorophyll-*a*, obtained from determinations in four seasons during 1995.)

Lake	Total P		PO ₄ -P		NO ₃ -N		SiO ₂		O ₂ depi. Aug	Chlorophyll- <i>a</i>		
	Jan	Aug	Jan	Aug	Jan	Aug	Jan	Aug		Jan	Aug	1995
Wastwater	3.8	2.7	<0.6	<0.6	360	343	2,380	2,200	–	0.58	1.00	0.8
Ennerdale Water	12.2	3.8	4.5	<0.6	343	323	2,670	2,410	–	0.77	1.33	1.2
Thirlmere (R)	7.2	2.7	<0.6	<0.6	227	219	1,700	1,420	–	0.59	2.26	1.4
Buttermere	6.1	2.7	<0.6	<0.6	203	146	1,820	1,450	–	1.36	1.50	1.5
Crummock water	8.7	4.6	1.3	<0.6	218	169	1,420	510	–	2.20	1.95	2.2
Haweswater (R)	11.0	6.5	1.8	<0.6	245	196	1,820	400	–	1.15	4.22	4.0
Coniston Water	8.0	8.4	2.4	0.9	395	335	1,140	100	–	1.45	5.72	4.0
Derwentwater	9.1	6.1	<0.6	<0.6	329	70	1,680	460	–	1.45	5.10	3.8
Grasmere	16.7	15.6	3.6	<0.6	445	61	1,920	1,020	+	0.61	10.7	7.2
windermere NB	19.0	14.4	9.7	<0.6	499	238	1,540	160	–	1.06	13.7	5.6
Loweswater	14.1	11.0	<0.6	<0.6	670	389	850	130	+	9.84	5.52	7.1
Bassenthwaite Lake	19.4	24.7	5.0	<0.6	546	223	2,320	910	+	1.14	11.6	8.9
Ullswater	13.7	9.5	3.6	1.0	329	179	1,120	130	var?	2.14	8.74	7.5
Windermere SB	33.1	36.9	24.0	1.1	538	108	1,550	370	var	1.50	29.6	10.4
Blelham Tarn	37.6	41.0	6.5	1.6	1,359	295	2,130	580	+	9.29	27.4	16.2
Esthwaite Water	28.1	32.7	12.8	1.0	1,027	364	2,540	160	+	3.61	41.1	21.8

R, NB and SB as in Table 1

Table published with permission of the Director FBA

the average lake catchment rainfall may be taken as 2,500 mm per annum and average runoff factor 0.75. The retention time in days is then

$$RT = (V \div A) \times 195$$

where V is in 10⁶ m³ and A is in km².

The complete calculation is performed by hydrological survey where the values for rainfall and inflow and out-flow values can be estimated by hydrological survey. In Table 1, the values for Windermere and Bassenthwaite

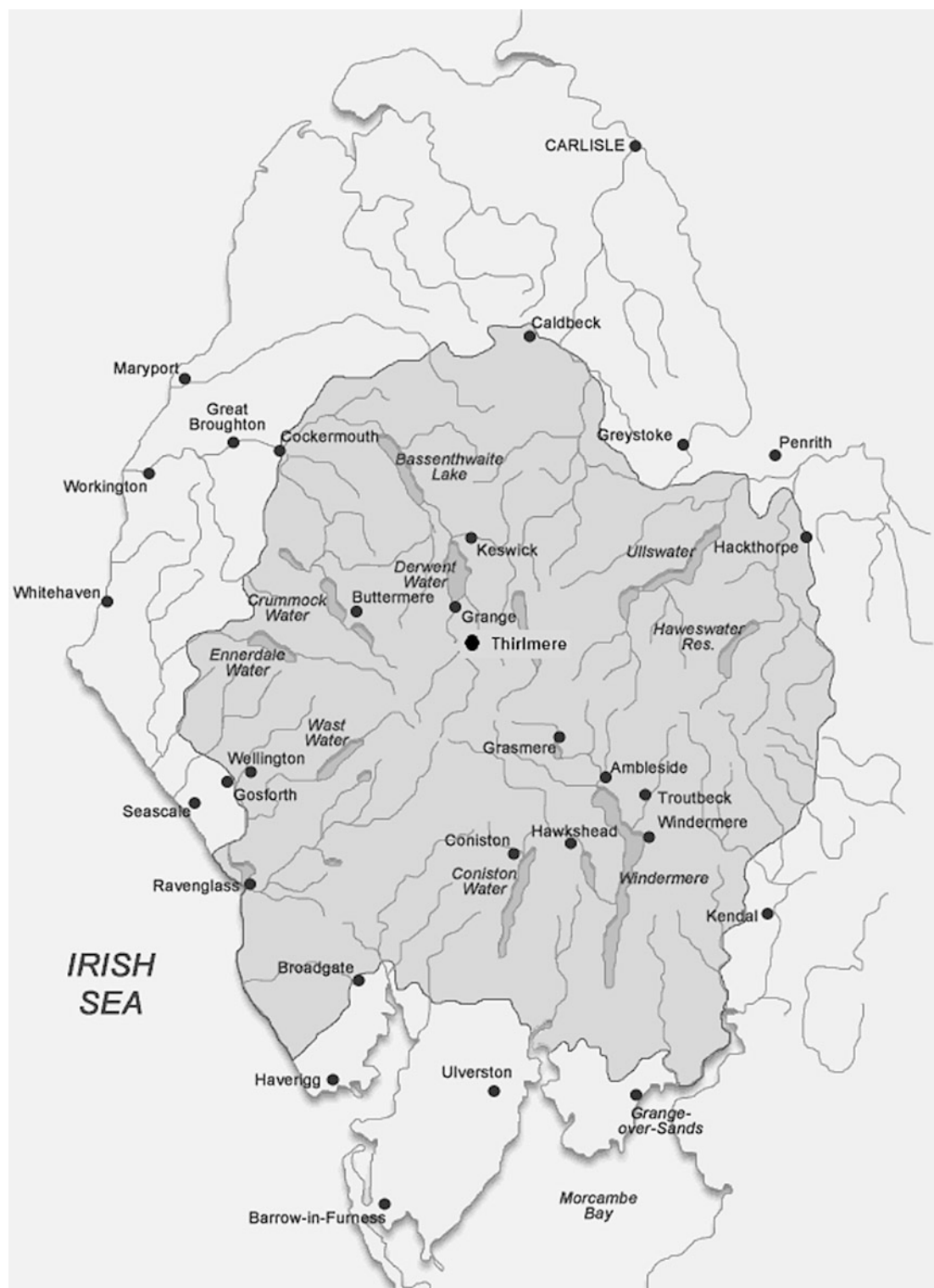
Lake have been calculated as 266 days and 23 days respectively as follows:

$$\text{Windermere: } RT = (314.5 \div 230.5) \times 195 = 266 \text{ days}$$

$$\text{Bassenthwaite } RT = (27.9 \div 237.9) \times 195 = 23 \text{ days}$$

Seasonal and long-term change

Individual lakes experience similar seasonal change but vary individual in long-term change. Weather has led to varying rates of sediment deposits in different lakes with high rates since the postglacial period (Figure 1).



English Lakes, Figure 1 The English Lake District, showing the drainage relationships of the lakes.

Sewage purification is of a high standard especially the effluent into Windermere where the removal of phosphate has had improved effect.

Seasonal changes, apart from varying vertical stratification, is expressed in annual cycles of nutrient concentrations and plankton.

Water balance

The hydrological water balance for Windermere has been developed for the period 1939 to 1984, for example, as follows:

Runoff $431 \times 10^6 \text{ m}^3$ per annum ranging from 110 to $689 \times 10^6 \text{ m}^3$ per annum

Total lake volume = 314.5×10^6 giving a mean retention time of approximately 9 months.

The range of water level is about 2 m and water is abstracted from the lake to the Manchester aqueduct.

Density stratification

Each lake experiences a temperature density layering during summer with differentiation into an upper epilimnion, an intermediate metalimnion with thermocline and a lower cold hypolimnion. The temperatures are lowest in January and February and the thermal stratification in April and May but may change slightly dependent on the Atlantic Gulf Stream.

Dissolved gases (O_2 CO_2 and pH)

Large season changes are found in oxygen and carbon dioxide. The changes in carbon dioxide affect chemical species are related to pH values. The largest concentrations are in the epilimnion, oxygen by phytoplankton photosynthesis, carbon dioxide by respiration and decomposition. Those of oxygen occur with yearly variation either in the metalimnetic (thermocline region) or in the late summer or autumn hypolimnion.

Plant nutrients

Season and annual changes in concentration of plant nutrient elements such as carbon, silicon, phosphorous, and nitrogen are carefully monitored. Any depletion of these elements may result from phases of algal growth especially in summer but least in winter. Estimates have been made of the annual input of phosphorous using river and sewage work flows and population. The estimated annual loading in the 1980s is about 1.72 g P per m^2 .

Heavy metals

Values of concentrations of zinc, lead, copper, cadmium, and mercury in the lake are low being less than $3 \mu\text{g per l}$. Sediments deposited during the last 130 years are enriched in the heavy metals. Rates of deposition have been measured directly in sediment traps.

Bacteria

Counts of bacterial concentrations are relatively recent but concentrations of the fecal *Escherichia coli* and

streptococci have been higher in areas where contamination by incompletely treated sewage (stormwater overflows) was still a problem although the small sewage works on the Windermere now produces an excellent effluent.

Algae

Blue-green algae in the lakes begin increasing in spring and peaking in summer depending on the cellular variable proportions of phosphorous which when low is an indicating limiting factor for growth.

Bottom-living algae (benthic) occur attached or free on various substrata in littoral areas that receive enough illumination.

Benthic bottom-living invertebrates are broadly differentiated with depth into littoral, or sublittoral. Several have spread widely around the lakes. The sublittoral community was surveyed in Windermere in 1934–1935.

Macrophytes and zooplankton

Macrophytes grow in a depth-range of the littoral with sufficient illumination in bays and shallows protected from wave effect and sediment. Surveys since 1913 in Ullswater have recorded flora of 20 submerged microphytes. Zooplankton community is important for food for young fish and surveys have shown a widely distributed specious in all Cumbrian lakes. Surveys in 1921 in Ullswater have recorded a widely distributed specious.

Fishes and water birds

A total of some 18 species of fishes are found in the lakes including brown trout, arctic char, perch and pike according to surveys carried out since 1940. Changes of poth perch and pike have been reported influenced by human removals or predation.

The wildfowl population has been monitored since 1967 which showed that the highest total counts are obtained in the winter months and for four species of duck since 1978 averaging a total of 2,647 in Windermere alone, coot adding a further 1,168 birds. For the goldeneye Windermere is a site of national importance with over 200 birds recorded in.

In 1970–1975 the lakes annual population of growing ducklings was estimated to consume some 2.6 t of fish per year. There is also some consumption by cormorant and heron. Recreation use of the lakes has had an effect on the bird conservation in both summer and winter.

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[Droughts and Water Management in England and Wales: With Particular Reference to Reservoirs and Lakes](#)
[Fens, England](#)
[Great Lakes, North America](#)
[Great Salt Lake](#)
[Reservoirs in Great Britain](#)

ESTUARINE HYDROLOGY

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Introduction

The word estuary is of sixteenth century origin and originated from the Latin *aestuarium*, which means marsh or channel, and this is derived from the Latin *aestus*, meaning tide or billowing movement. Estuaries are transitioning environments between the land and the

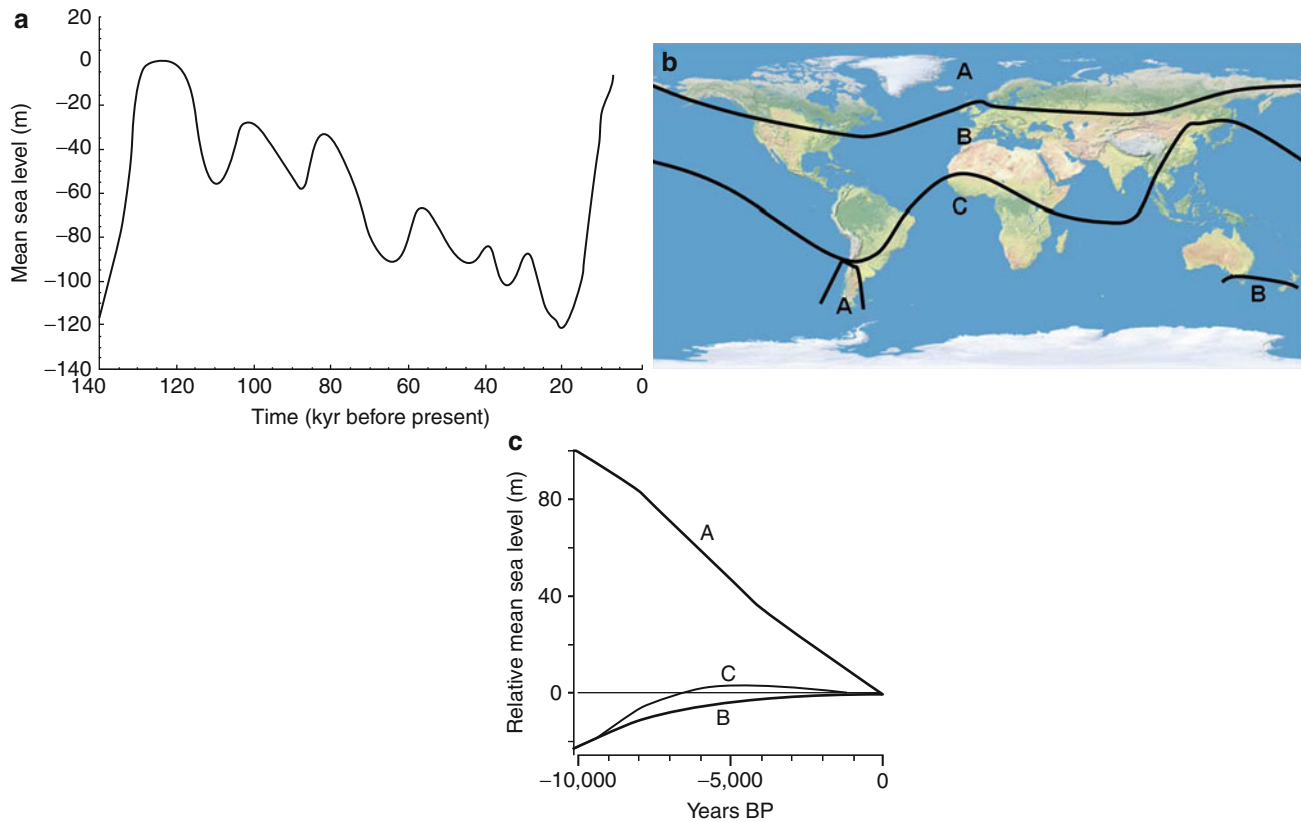
ocean, where fresh water coming from the rivers mixes with saline oceanic water. This river inflow need not be perennial. There are several definitions of estuaries. For freshwater scientists the main thing is to define the head of an estuary; in one definition, this is the salinity limit; in another definition, this is the tidal limit; and in still another definition, it is the source of the fluvial sediment. For coastal scientists and oceanographers, the mouth of an estuary, i.e., the point where an estuary ends, is also ill-defined. It can be a geographic feature or the seaward edge of a tidal plume in the open ocean.

Whatever the geographical definition, an estuary is a zone of transition with gradients in salinity, sediment characteristics, turbidity of the water column, chemical composition including nutrients, dissolved gases, and trace metals and in diversity and productivity of species of animals and plants. Estuarine waters are commonly more biologically productive than the oceanic waters. In addition, estuaries are strategic locations for human development; nearly 69% of the largest cities in the world are located on river estuaries. The scientific understanding of estuaries is thus of great practical importance.

An estuary is never at a steady state. Its bathymetry is continuously evolving. Forced by tides, waves, and river inflows, estuarine water is continuously moving and with it, its ecology is also continuously evolving. Some largest estuaries may have the additional direct influence of winds on the local circulation such as the Amazon River. The resulting physical and biological features of an estuary and its ecosystem health are determined by the time scales of the processes controlling the movements of water and sediments and the ecological processes in the water and on the bottom.

Genesis and geomorphologic time scales

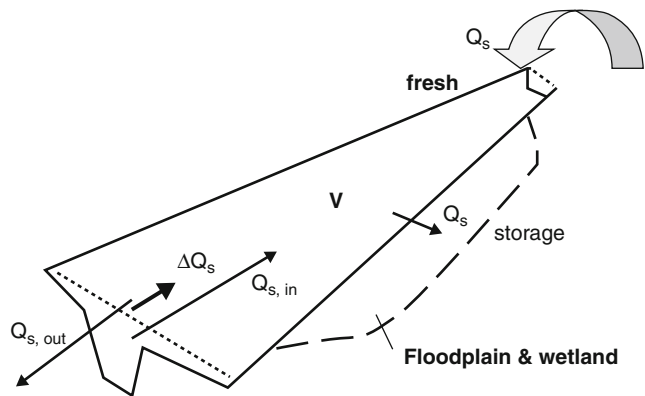
The physical features of an estuary are determined firstly in a time scale of centuries from the recovery of the global mean sea level (MSL) from the last glaciation (i.e., eustatic variation) and the tectonic movements that resulted (i.e., isostatic variation), and secondly in a shorter time scale from human-induced changes in river discharge Q_r and riverine sediment inflow Q_s . Global MSL was 120–130 m lower 20,000 years ago than at present (Figure 1a). The melting of the ice resulted in a rebound of the continental plates relieved of the pressure of ice glaciers. As a result the relative MSL varied spatially in three zones (Figure 1b) of, respectively, ongoing decrease, relative stability, and ongoing small increase (Figure 1c). The global MSL has been fairly constant for the last 6,000 years. It is now at a high stand level that was last reached about 120,000 years ago. Old river and flood plains became flooded by rising seas; estuaries were formed as they filled with sediment originating from the watershed and from the sea; watershed sediments were brought in by rivers and coastal sediments were brought in by tides and storms.



Estuarine Hydrology, Figure 1 (a) Time series plot of the global mean seal level over the last 140,000 years. (b) The approximate distribution of the coasts that followed one of the three typical relative mean sea level curve types A, B, and C as shown in (c) (Redrawn from Wolanski et al. (2009)).

Thus most estuaries have not reached a steady state yet; they are still evolving. They have an age; they all started young, many have reached maturity though not the fjords, and some have reached old age, which means that they cannot accommodate any additional sediment. The extra sediment is carried seaward to be dispersed at sea or to form a delta. An old estuary can be rejuvenated when a major river flood creates a new river mouth.

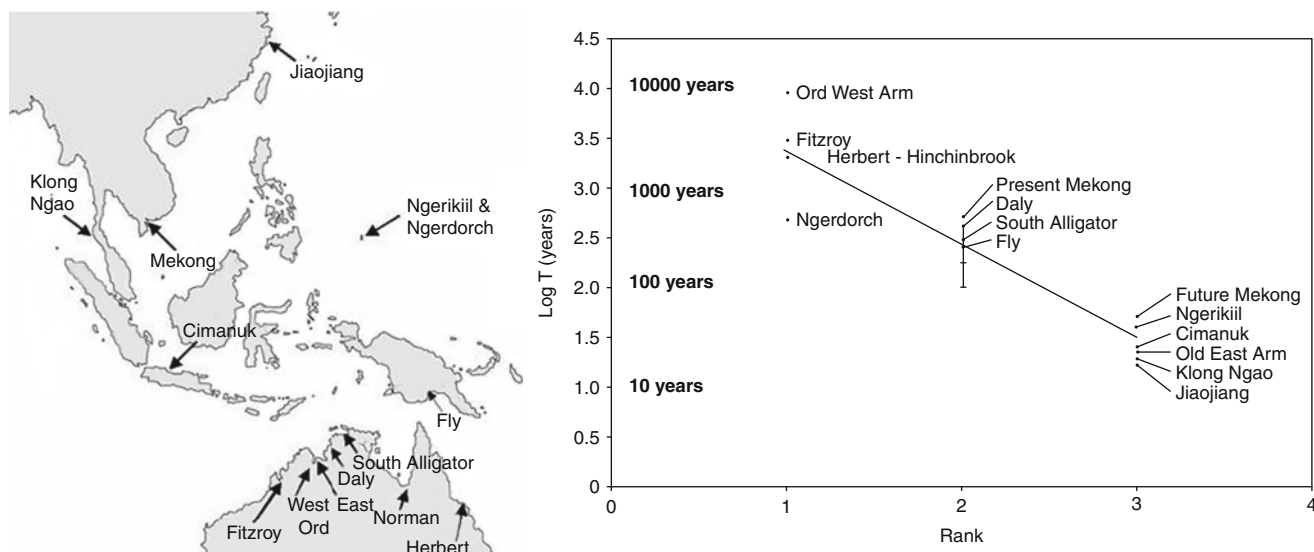
As sketched in Figure 2, the infilling of an estuary of volume V is controlled by the inflow of riverine sediment $Q_{s,in}$, the net balance ΔQ_s between seaward ocean flux $Q_{s,out}$ and the landward sediment flux from coastal water $Q_{s,in}$, and the sediment flux to lateral storage in the flood plains $Q_{s,storage}$. The geomorphologic age of an estuary is the time it takes for the net sediment flux to fill the volume V . The aging of an estuary can be greatly accelerated by human activities in the watershed, mainly land clearing. As an example this geomorphologic age T was estimated for a number of macro-tidal muddy estuaries in the Pacific region (Figure 3); T varies between several thousand years for estuaries that are non-impacted by human activities (rank 1), to several hundreds of years for estuaries that are moderately impacted by land clearing in the watersheds (rank 2), to only several tens of years for estuaries



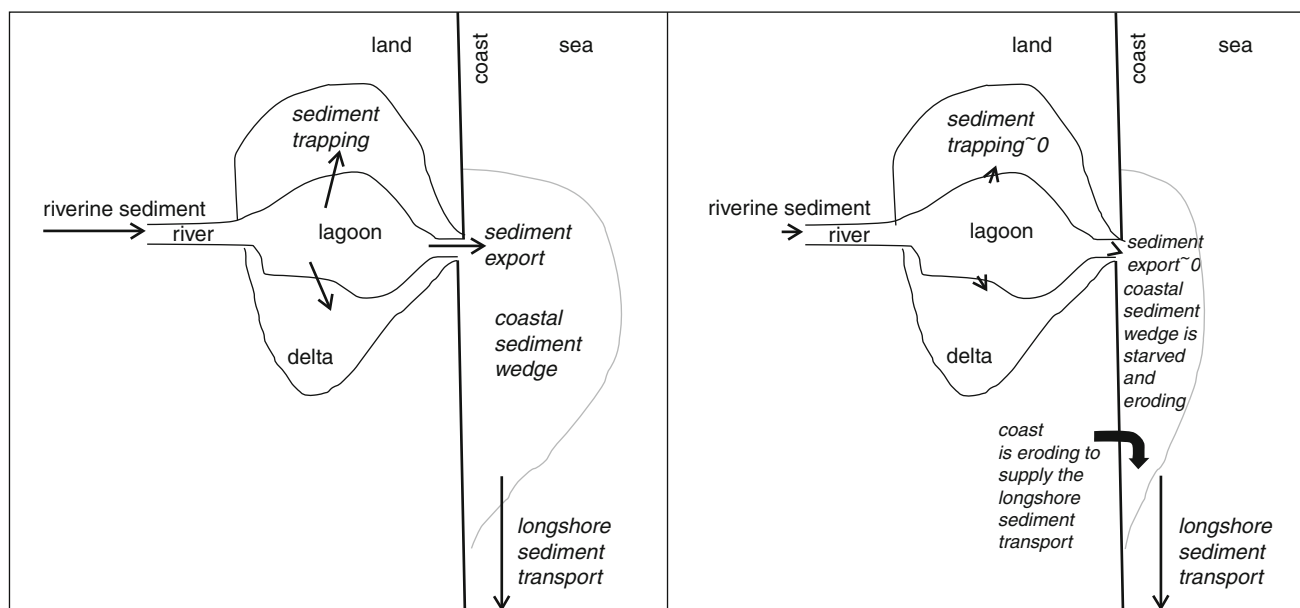
Estuarine Hydrology, Figure 2 A sketch of the net sediment budget in an estuary.

that are severely impacted by land clearing in the watersheds (rank 3), illustrating the rapid acceleration of the aging of estuaries by siltation due to land clearing in the watersheds.

Dams on the other hand can trap sediment in reservoirs and thus prevent sediment to reach the estuary, which



Estuarine Hydrology, Figure 3 The geomorphologic age of macro-tidal, muddy estuaries in the Pacific.



Estuarine Hydrology, Figure 4 A sketch of the sediment budget in the micro-tidal Nile and Colorado deltas (*left*) before and (*right*) after dam construction.

slows down the estuarine aging process. This is particularly the case for micro-tidal and tideless estuaries. Before the mega-dam was constructed some riverine sediment was trapped in the estuary that usually comprised a lagoon and a delta; the rest was exported to the sea (Figure 4a). The mega-dams in the Colorado and the Nile rivers have stopped all (most) river floods' export of water and sediment to the sea (Figure 4b) and significantly decreased the inflow of sediment to the estuary. The

channels are silting slower, i.e., aging slower, than before due to lesser sediment inflow from the dam, while the coast is eroding.

However, in macro-tidal estuaries, large dams can accelerate the aging of estuaries. This is because they can decrease or even stop large river floods; this prevents seaward flushing of estuarine sediment and accelerates tidal pumping of coastal sediment landward into the estuary; these result in siltation and thus aging the estuary.

At the same time however the coast becomes starved of sediments, which are exported by waves and currents in the open sea; as a result, the coast erodes.

Sediment dynamics time scales

Estuarine sediments are of two types: cohesive sediments (also called mud or clay) have a mean particle size $d_{50} < 4 \mu\text{m}$; non-cohesive sediments (sand) have a $d_{50} > 64 \mu\text{m}$. Silt has a d_{50} in between those of mud and sand; it is weakly cohesive.

The sediment dynamics depend on the currents, the salinity, the type of sediment, and the biology. Sand is mainly carried along the bottom and very close to the bottom. Mud is mainly carried in suspension within the water column.

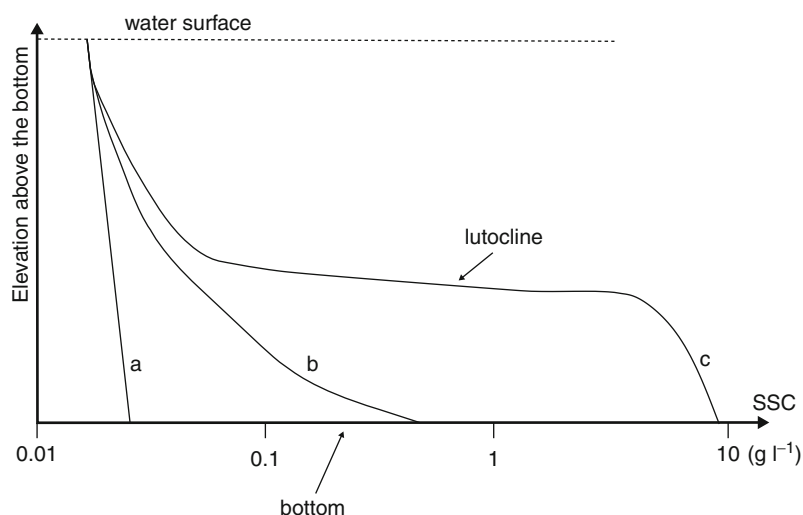
There are several models, pioneered by engineers, to calculate the sand transport as bed load. The models generally assume either that the sand moves as a creeping movement of layers along the bottom or that the sand particles are rolled and tossed over the bottom in a process called saltation. The models are based on laboratory studies and estimate the bed load transport as a function of the mean particle size d_{50} , the current-induced stress, a threshold stress for bed load to commence, and the difference in density between the water and the sediment. They yield at best order-of-magnitude estimates and thus must be used with caution. Sand is often mixed with mud and even if the sand is the dominant fraction, the clay particles modify the bed load by a factor of 2–4.

Cohesive sediment (mud) behaves differently than non-cohesive sediment (sand) because it forms flocs typically 100–200 μm in size. Flocculation is initiated by salinity ions that cause electronic forces between the small sediment particles and greatly enhanced by the bacteria and plankton that, through the production of transparent

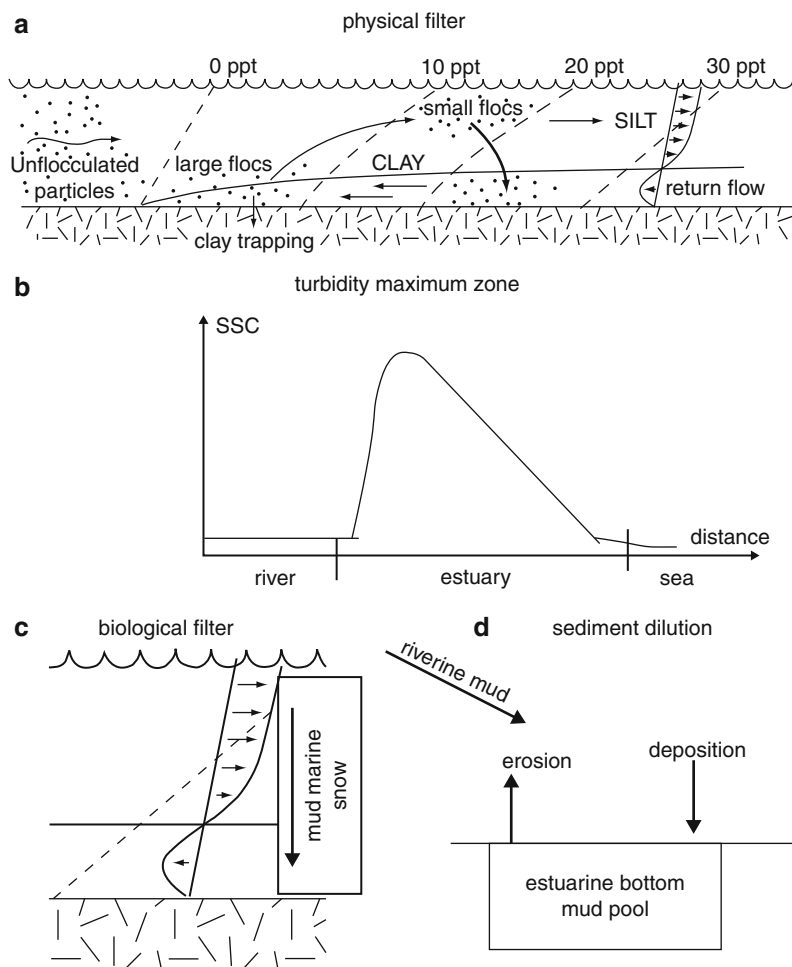
exopolymer particles (i.e., a mucus), aggregate flocs to form extremely large flocs (commonly 1,000 μm in size) and are called marine snow flocs. In very turbid waters ($\text{SSC} > 500 \text{ mg L}^{-1}$), marine snow is scarce; in less turbid waters (typically $\text{SSC} < 100 \text{ mg L}^{-1}$), marine snow is common. The biology also controls the erodibility of the bottom sediment because algae mats stabilize the bottom sediment and animal burrows may loosen the sediment and facilitate erosion. There are models, pioneered by engineers, to calculate the mud transport as a suspended load. They are largely based on laboratory experiments and they generally fail in the field because the laboratory experiments cannot account for the biology in the field.

The vertical profile of suspended sediment concentration (SSC) takes many shapes, from vertically nearly well-mixed (line a in Figure 5), to smoothly increasing with depth (line b), to a step structure called the lutocline for $\text{SSC} > 5 \text{ kg m}^{-3}$ (line c). Because the suspended sediment increases the density of the water, the water density changes across the lutocline. This reduces the vertical diffusion coefficient K_z in the lutocline, in the same manner that a thermocline inhibits vertical mixing between the hypolimnion and the epilimnion. This helps preserve a fluid mud layer near the bottom.

Riverine mud in suspension commonly reaches the estuary unflocculated. On reaching the estuary, this mud flocculates as a result of the action of salinity and the biology (Figure 6a). Salinity-driven currents, tidal currents, and weaker cohesive forces of silt flocs as opposed to mud flocs generate a physical filter that sorts the silt from the clay (Figure 5a) and that creates a turbidity maximum zone (Figure 5b). Marine muddy snow forms a biological filter that inhibits the export of mud from estuaries (Figure 6c). Finally the riverine mud mixes with, and is diluted by, the estuarine mud through erosion and



Estuarine Hydrology, Figure 5 Three typical vertical profiles of suspended sediment concentration in estuaries.



Estuarine Hydrology, Figure 6 (a) The physical filter of fine sediment that generates (b) a turbidity maximum zone, i.e., a zone with the highest suspended sediment concentration (SSC); the SSC curve varies with the tides. (c) Biologically produced transparent exopolymer particles and fine sediment in suspension interact to produce muddy marine snow flocs that accelerate the settling of the mud and generate a biological filter inhibiting the export of fine sediment seaward. (d) Riverine mud is diluted by estuarine mud.

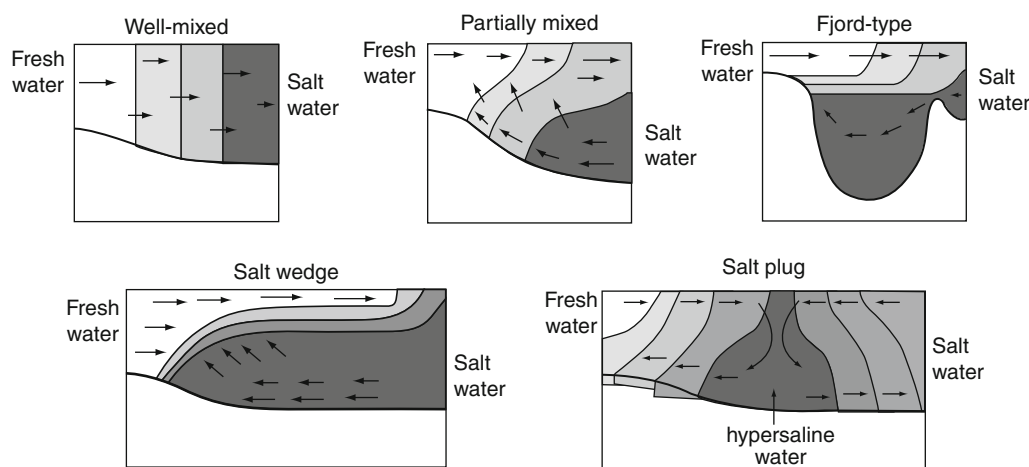
sedimentation as a result of floods, waves, tides, and storms (Figure 6d). In some estuaries, the tidal currents are larger during the rising tide than during the falling tide; in those estuaries, the tides pump the sediment landward. These processes greatly increase the residence time in the estuary of the riverine mud and its particulate pollutants and nutrients.

If the estuary is sandy, the sediment is also trapped in the estuary and the trap is also leaky, with sediment imported both from the sea and from the rivers and exported offshore during large river floods. The evolution of a sandy estuary geomorphology is difficult to predict because of the difficulties in measuring sandy sediment fluxes. Observations suggest that the dominant forcing functions controlling the movement and trapping on sandy sediments in estuaries are the oceanography (tidal dynamics and storms) and the hydrology (floods).

Classification based on geomorphology and on water circulation

Estuaries may be classified upon their geomorphology or physical oceanography.

The estuarine types based on the geomorphology are mainly (1) drowned river valleys, (2) lagoon-type or bar-built, (3) fjords. Most of the drowned river valleys were formed with the sea level rise on low and wide coastal plains (e.g., Chesapeake Bay, Tampa Bay, and Delaware Bay). The lagoon types are semi-isolated from coastal waters by barrier beaches and some lagoons are extremely large (e.g., Lagoa dos Patos in Brazil that is 242-km long, and the Mirim Lagoon in the border between Brazil and Uruguay that is 290-km long, and the well-known Venice Lagoon, famous in human history). These estuaries have only a few narrow inlets allowing the interaction between the estuary and the coastal zone. The fjords were formed in



Estuarine Hydrology, Figure 7 Classification of estuaries based on the physical oceanography.

deeply eroded valleys caused by the glaciers; many of them have shallow areas near the estuarine mouth, and thus restricting the water flow. Fjords often have lower temperatures than coastal waters (e.g., the deepest fjord is the Sognefjord in Norway with depths up to 1,300 m, and the largest fjord is Scoresby Sund in Greenland that is 110 km long).

The classification based on the estuarine circulation is based on the vertical distribution of salinity in the estuary, and the types are (1) salt wedge, (2) partially mixed, (3) well-mixed, (4) fjord-type, and (5) salt plug (Figure 7). In salt wedge and fjord-type estuaries, the river inflow greatly exceeds tidal currents, freshwater moves as a distinct surface layer, and a sharp salinity interface separates the fresh/brackish water on top from the saline water underneath. In partially mixed estuaries, the tidal currents only slightly exceed river inflow, and thus cause more vertical mixing, which reduces vertical salinity gradients. Well-mixed estuaries are dominated by tidal mixing, thus the vertical salinity stratification is negligible. Salt plug estuaries occur in the dry climates, where evaporation greatly exceeds river inflow, resulting in higher salinity in the estuary than at the mouth.

Biological implications of sediment transport

At high SSC (highly turbid), there is nearly complete darkness. Typically, for suspended sediment concentration (SSC) = 0.2 g L^{-1} , visibility < 30 cm; for SSC = 1 g L^{-1} , visibility < 1 cm. The plankton in these turbid waters can only photosynthesize for the short time that it is brought to the surface by turbulence. The benthos has no such opportunity; it stays in complete darkness as long as the water stays turbid. In addition, even in the absence of suspended sediments, light is attenuated with depth depending on the plankton (shading effect) and on dissolved organic matter (DOM).

Mud also affects pollutants (such as PCBs and heavy metals) and nutrients (particularly phosphorus, less so for nitrogen) because these particles are readily absorbed

on the mud due to the electric and colloidal forces on the clay particles. Thus pollutants can stay trapped hundreds of years on settled mud and are released when the mud is resuspended. Suspended mud is important in absorbing dissolved nutrients and largely making it unavailable by the plankton. This is quantified by the partition coefficient K_d

$$K_d = \text{mass absorbed on particulates} / \text{Total mass} \quad (1)$$

and this was quantified by Middelburg and Herman for estuaries in Europe; they found at suspended particulate matter (SPM) of 10 mg L^{-1} about 10% of the organic carbon may be present in particulate form, and this was about 50% at SPM of 100 mg L^{-1} and 80% at SPM of 400 mg L^{-1} . Phosphorus is also readily absorbed on suspended mud and nitrogen less so. Thus, in muddy estuaries, the classical stoichiometry ratios for dissolved inorganic nutrients C:N:P = 106:16:1 may not hold, and this invalidates the use of aquatic ecosystem models based on stoichiometry.

In muddy estuaries, most heavy metals and a number of pollutants such as PCBs and POPs are nearly totally sequestered on mud particles; they are thus extremely slowly flushed out of polluted, muddy estuaries, and are thus a legacy of pollution that may last many decades, and even centuries, after the pollution source was stopped. This is the case for instance of Boston Harbour in the USA and the Elbe Estuary in Germany.

The impact of riverine nutrients on an estuary is very different for a sandy (clear water) estuary where the nutrient is readily bioavailable and light penetration allows photosynthesis, than for a muddy (turbid) estuary where much of the nutrient, especially phosphorus, is absorbed on the mud and photosynthesis is inhibited by the lack of light.

Tidal wetlands

The vegetation in tidal wetlands plays an important role in controlling the net sediment flux in or out of an estuary.

These wetlands were originally non-vegetated intra-tidal mudflats exposed at low tide and inundated at high tide. These mudflats commonly have a tidal creek that focuses the largest currents in the creek; the currents remain small in the surrounding flats where sediment can thus accumulate. These non-vegetated mudflats are often unstable and are readily modified by storms. All this changes drastically when the sediment accumulation results in the substrate rising above mean sea level. At that stage the vegetation establishes itself, consisting typically of salt marsh plants in temperate climate and mangroves in tropical climates. Through its roots below ground the vegetation helps stabilize the tidal creek; through its structure above ground the vegetation accelerates sedimentation by slowing down the water and thus enabling the suspended sediment entering the intertidal areas at rising tide to deposit. The difference between the sediment that comes in at rising tide and the sediment that goes out at falling tide is the sediment trapped in the tidal wetlands. This role of vegetation is crucial in enhancing sediment trapping in estuaries; for instance a mangrove that covers 3.8% of the river drainage area traps 40% of the riverine mud inflow; a salt marsh where plant height exceeds 8 cm may enable sedimentation at a rate of up to 8.2 cm year⁻¹; the rate of sedimentation of British salt marshes averages 4.3 mm year⁻¹ and a similar result is also found in US salt marshes. Storms may disturb this trend in the short-term.

Tidal wetlands comprise globally mainly mangroves and salt marshes. Mangroves worldwide cover an area of about 240,000 km² and are the dominant coastal wetland in subtropical and tropical regions where frosts do not occur. Salt marshes are distributed worldwide, mainly in areas subject to frosts where mangroves do not grow and in the higher grounds next to mangroves; thus they are most common in middle and high latitudes; their vegetation comprises mainly salt-tolerant grasses and rushes. Mangroves and salt marshes vegetation exhibit zonation patterns whereby the vegetation is the thinnest in the areas of lowest elevation where sediment accretion occurs. A mild slope in the vegetated wetlands forms a drainage pattern toward the tidal creek.

The importance of tidal wetlands to the estuarine ecosystem is not limited to sequestering nutrients and pollutants. Tidal wetland vegetation converts excess nutrients in the flowing waters into plant biomass; in turn this plant biomass supports an ecosystem. Organic detritus such as plant litter is exported from the wetlands to the estuary. The wetlands also provide a nursery for fish and crustaceans that come in from the estuary – and the sea for migrating species – to feed and shelter within the salt marsh and later return to the estuary or the sea; this forms an important exchange of organic nutrients between the tidal wetlands on the one hand and estuarine and coastal waters on the other hand. The nutrient outwelled from tidal wetlands increases the estuarine plankton community, which in turn supports commercial fisheries of fish and shrimps, the success of which is closely linked to tidal wetlands.

The water transport time scales

The movement of water in an estuary is controlled by the tides, the river inflow, rainfall and evaporation, the wind, and events at sea such as storms. The multitude and variety of these factors, their interaction with the often shallow and highly irregular bathymetry, contribute to a complex nonlinear and unsteady three-dimensional hydrodynamics.

Models of varying complexity can be used order to describe and quantify the transport of pollutants and the renewal of water.

Box models, in particular, are often used for a quick assessment of the flushing capability of an estuary. In the simplest approach, the estuary is modeled as a single box. Assuming steady state, the turnover time or flushing time T of the estuary can then be estimated as

$$T = V/Q \quad (2)$$

where V is the water volume in the estuary and Q is the total freshwater input. In tidal estuaries, the amount of water exchanged at each tidal cycle is estimated as the difference of water volume between high and low tides, the so-called tidal prism V_p (Figure 8a). Using this tidal prism flushing model, a fraction

$$r = V_p/V \quad (3)$$

of the estuary water is assumed to be renewed by ocean water at each tidal cycle and the turnover/flushing time can be expressed as

$$T = \tau/r \quad (4)$$

where τ is the tidal period (e.g., 0.5 day for solar semi-diurnal tide and 1 day for solar diurnal tide).

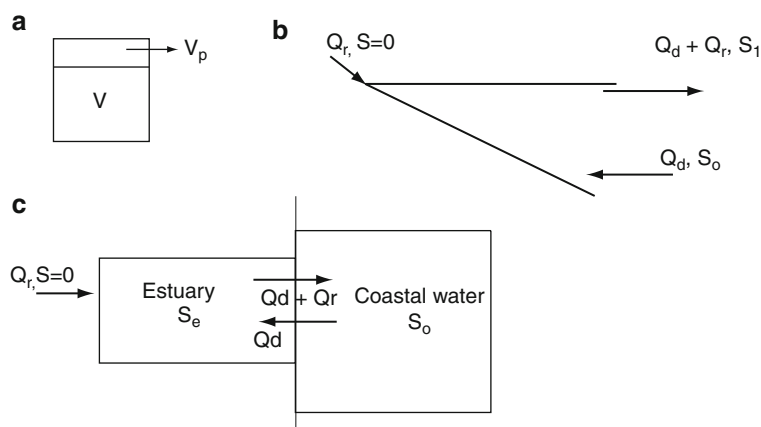
The above models provide a very crude description of the exchange processes between the estuary and the coastal sea region. Very often, the net water exchange results from the difference between two opposite water fluxes corresponding to the inflowing sea water and the outflowing estuarine water. In the gravitational circulation model (Figure 8b), these water fluxes are associated with the two-layer baroclinic circulation typical of partially mixed estuaries (Figure 7). In well-mixed broad estuaries, the two opposite fluxes can occur simultaneously in the horizontal plane (Figure 8c).

Using the configuration of the LOICZ model shown in Figure 8c, the steady-state water balance in the estuary requires that the outflowing flux be the sum of the freshwater input in the estuary Q_r and the seawater inflow Q_d . Expression (Eq. 2) of the turnover time can then be generalized with $Q = Q_r + Q_d$.

As steady state, the rate Q_d can be calculated from the salt balance

$$Q_d \Delta S = Q_r S_{out} \quad (5)$$

where S_{out} is the salinity of the estuarine outflow and ΔS is the excess salinity brought by the seawater, i.e.,



Estuarine Hydrology, Figure 8 (a) The tidal prism box model (*side view*); (b) the gravitational circulation box model (*side view*); (c) the LOICZ box model for a vertically well-mixed estuary (*plan view*).

$$\Delta S = S_o - S_e \quad (6)$$

where S_o is the salinity in coastal waters and S_e is the estuarine salinity. Setting $S_{out} = S_e$ leads to the

$$T_r = V / Q_r (1 - S_e / S_o) \quad (7)$$

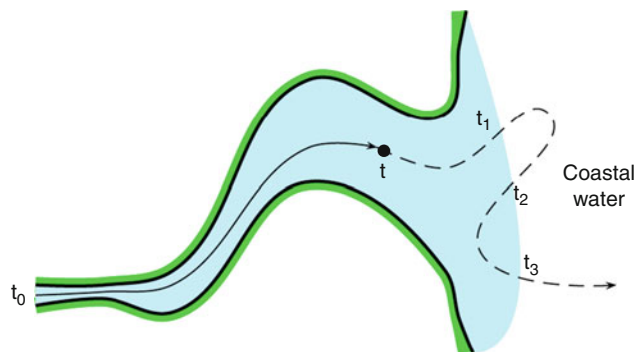
The LOICZ method for the derivation of the renewal time is similar but S_{out} is taken as the mean salinity in the outer estuary, which is estimated as

$$S_{out} = 0.5 (S_o + S_e) \quad (8)$$

The LOICZ box model is simple and easy to use and has been used in about 200 estuaries worldwide. Rainfall, groundwater, and evaporation can also be added if needed. If the system is not vertically well-mixed, a stacked box model can be used with a box on top representing the upper layer and a box on the bottom representing the lower layer and the vertical fluxes are calculated from salinity data.

The above box models, which can be further refined, are useful as a first approach but have serious limitations because they only capture some of the physics (e.g., Sheldon and Alber, 2006). They are all based on a steady-state balance, assume complete and immediate mixing in the estuary, poorly account for the diffusive fluxes between the estuary and the coastal sea, and ignore the spatial variations inside the estuary.

The flushing rate and the transport of pollutants also depend on the internal circulation within the estuary driven by the density difference generated by changes in salinity and temperature. This difference in density is determined by vertical mixing by the wind, by boundary-generated turbulence, and by turbulence in the water currents driven by tides, wind, and river inflow. Vertical mixing is parameterized by the vertical eddy diffusion coefficient K_z , which is minimal at the level of the density interface (i.e., the pycnocline). Additional mixing also results from turbulence generated at the banks of the



Estuarine Hydrology, Figure 9 Path followed by a particle in the estuary from the upstream boundary to the coastal sea. At time t , the age of the particle is $t-t_0$, its residence time is t_1-t , its transit time is (t_1-t_0) , its exposure time is $(t_1-t) + (t_3-t_2)$.

estuary and by secondary flows around shoals and islands, as well as three-dimensional flows in meanders.

A proper description of estuarine dynamics and the assessment of the associated transport rates require therefore two-dimensional (either in the horizontal or in the vertical plane) or even three-dimensional models. Such models are elegant but they still carry uncertainties in term of the hydrodynamic conditions and the fate of tracers at the open boundaries as well as in quantifying the turbulent diffusion. Also the influence of small scale features and the possible occurrence of sandbanks that fall dry at low tide require special numerical treatments. Unstructured grid models permitting local refinements of the computational mesh where necessary and taking into account external influences in a natural way are particularly suited for such studies (de Brauwere et al., 2011).

The refined description of the water circulation provided by high-resolution numerical models gives also access to more representative transport timescales, namely, the age, the residence time, the exposure time,

and the transit time, superseding the poorly defined flushing time, turnover time, and renewal time. These timescales are best introduced by considering the fate of a water parcel or of a tracer particle (Figure 9).

The age of a particle measures the time elapsed since it entered the estuary. The age reflects therefore the past history of the particle. With the residence time, one looks forward in time: The residence time is time necessary for a water parcel originally in the estuary to leave the domain for the first time. The exposure time is similar to the residence time but allows for particles to return into the estuary after leaving it (with reversing tidal currents, for instance); the exposure time of a particle originally in the estuary is the total time that the particle will spend in the estuary. The transit time of a particle is defined as the sum of the age and the residence time (Takeoka, 1984; Zimmerman, 1988).

Because of mixing, different particles introduced in the estuary at exactly the same location and at the same time will follow different trajectories and are therefore characterized by different timescales. Distributions of age, residence time, exposure time, and transit time must therefore be considered, although one can usually content oneself with their average value in most cases.

The Constituent oriented Age and Residence time Theory (Delhez et al., 1999, 2004) provides the appropriate framework to compute the above timescales in an Eulerian framework, in a suitable form to be easily implemented in existing numerical models. The mean residence time ϑ , for instance, can be obtained as the solution of the advection-diffusion problem

$$\frac{\partial \vartheta}{\partial t} + 1 + \nabla \cdot (v\vartheta) + \nabla \cdot (K \cdot \nabla \vartheta) = 0 \quad (9)$$

(where t is the time, v is the velocity, and K is the diffusion tensor) with boundary conditions prescribing that ϑ vanishes at the open boundaries. To compute the exposure time, the same equation must be solved but the model domain must be extended offshore to describe the coastal circulation and describe the possible return path of tracers.

Exact analytical solutions are available if the estuarine cross-section is constant along the channel, which is often a restrictive assumption.

Table 1 compares transport timescales computed using different approaches in various estuaries. Large differences between the various time scales exist for the same estuary, highlighting the importance of defining precisely the particular time scale needed for particular applications.

When the estuary is density-stratified, the residence time of water in an estuary also depends on the internal circulation within the estuary driven by the density difference generated by changes in salinity, temperature, and suspended sediment concentration. This difference in density is determined by vertical mixing by the wind, by boundary-generated turbulence, and by turbulence in the water currents driven by tides, wind, and river inflow. Vertical mixing is parameterized by the vertical eddy diffusion coefficient, K_z , which is minimal at the level of the density interface (i.e., the pycnocline). Additional mixing also results from turbulence generated at the banks of the estuary and by secondary flows around shoals and islands, as well as three-dimensional flows in meanders.

When the bathymetry is complex, e.g., with meanders or shoals, the water circulation in estuaries also varies markedly across the width, forming regions of convergence (where floating matter accumulates) or divergence (where floating matter disperses swiftly). This also modifies the water transport time scales.

Ecological implications of the transport time scales

For a given estuary, the geomorphologic time scale determines the estuarine bathymetry. The habitats, including tidal wetlands and rocky zones, are determined by the underlying geology as well as the geomorphologic time and sediment transport time scales. The fate of nutrients and pollutants is determined by the habitats and the sediment and water transport time scales. In turn, all of these parameters determine the ecology of the estuary.

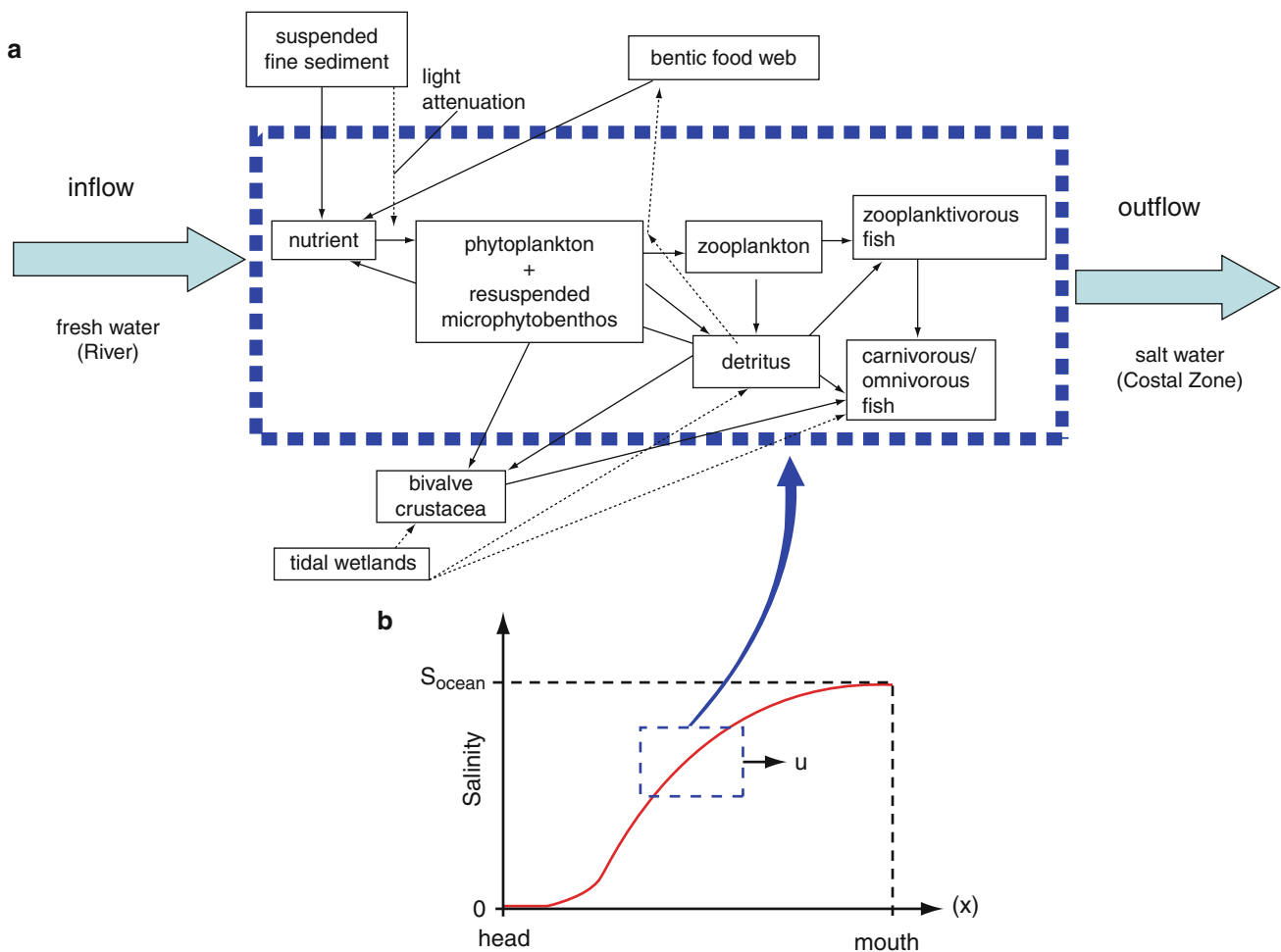
Estuarine Hydrology, Table 1 Example of the water transport times (in days) for various vertically fairly well-mixed estuaries

	Renewal time (LOICZ box model)	Average residence time (CART, 1D)	Average exposure time (CART, 1D)	Average residence time (numerical model)
Curimataú Estuary (Brazil)				
Neap tides	0.5–0.9	0.1–0.6	1.2–1.7	–
Spring tides	0.5–1.4	0.02–0.1	1.4–2.2	–
Hudson Estuary (USA)				
Neap tides	4.3–5.3	1.2–2.3	6.2–6.7	8–10
Spring tides	4.2–5.2	1.3–2.3	10.1–11.2	8–9
Conwy Estuary (UK)				
Neap tides	31.8–35.3	10.2–12.8	74.6–81.1	–
Spring tides	28.1–31.2	6.0–7.7	109.5–120	–
Mersey Estuary (UK)				
Typical flow range	3.5–7.8	0.5–1.7	35.4–99.5	1–6.3
Scheldt Estuary (Belgium, The Netherlands)				
Average conditions	23.8–75.2	5.3–10.4	204.1–302.5	5–70

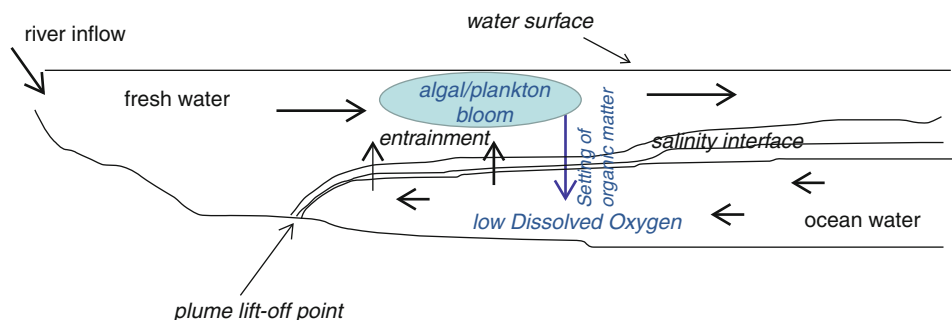
In a vertically well-mixed estuary, the nutrient is cycled between phytoplankton and resuspended microphytobenthos, zooplankton, bivalves and crustacea, and fish (Figure 10). Dying organisms, excreta, and leftovers from messy eaters become detritus that is recycled, some through the microbial loop. As shown by the dotted lines, tidal wetlands provide detritus and juvenile fauna to the estuary. This ecosystem is not closed; in fact, it is supported by an inflow of nutrients, fish, and plankton from the sea and the watershed (the river and groundwater); some of that matter is also lost by export to the sea. The level of processing of these various inflows depends on a large number of parameters including the climate, the habitats, the intensity of the inflows, the water and sediment transport time scales, and the partitioning coefficient. In turn

the estuarine ecosystem is determined by these physico-chemical attributes and the ecological niches.

The same nutrient cycling may prevail in the top layer of a salt wedge estuary (Figure 11). However, the situation is very different in the bottom layer, which is enriched by organic matter falling down from the top layer especially if the top layer supports an algal or plankton bloom. This organic matter decays in the bottom layer and extracts dissolved oxygen from the water column. As the bottom layer is not in contact with the water surface and the salinity stratification completely shuts down the turbulence at the salinity interface, oxygen cannot be supplied from the top layer. Oxygen can only be supplied by ventilation, i.e., the import of oxygen by currents bringing in oceanic waters in the bottom layer. This bottom layer becomes



Estuarine Hydrology, Figure 10 (a) A typical pelagic food web in a vertically well-mixed estuary. It comprises a waterborne ecosystem (the blue box) that is moving with the water currents, thus comprising an inflow into the estuary and an outflow from the estuary; it is flushed at a rate determined by the water transport time scales. It comprises also suspended sediment that is also varying in time at a rate determined by the sediment transport time scales. It comprises also a benthos and bottom dwelling animals living in habitats that are varying in time at a rate determined by the geomorphologic time scale. (b) Typical salinity distribution increasing from the head to the mouth. The waterborne ecosystem (blue box) is advected seaward, thus remaining only in transient contact with the substrate and the tidal wetlands, and at the same time it is subject to increasing salinity as a result of mixing. As it moves toward the head of the estuary, the waterborne ecosystem also encounters different habitats.



Estuarine Hydrology, Figure 11 A sketch of the water circulation in a salt wedge estuary. Organic detritus settles from the top layer where it is produced by an algal/plankton bloom. By decaying in the bottom layer, this material extracts dissolved oxygen from the water column. Low dissolved oxygen commonly results in the bottom layer. If the inflow rate of dissolved oxygen by oceanic inflow in the bottom layer is smaller than the consumption rate of dissolved oxygen by the decay of organic matter in suspension and on the bottom, anoxia can result.

anoxic if the oxygen consumption rate is larger than the rate of import of oxygen from oceanic water.

Partially mixed estuaries may suffer less from bottom water anoxia than salt wedge estuaries because the salinity stratification is less intense and does not completely shut down the turbulence; some vertical mixing remains and as a result additional oxygen is provided to the bottom layer by vertical diffusion of oxygen from surface waters.

Each of these physicoecological relationships is affected by the human impact. A most common indicator of a severe human impact is that the bottom layer of vertically stratified estuaries – which has the largest water transport time scales – becomes anoxic or hypoxic. Estuaries with a small value of the water transport time scales have less time for the dissolved oxygen to be depleted and for sediments to accumulate in the estuary; such estuaries are thus intrinsically more robust than poorly flushed estuaries.

Another indicator of the human impact is the increasing frequency of harmful algae blooms. High riverine loads of nitrogen and phosphorus into an estuary initially lead to a bloom of phytoplankton or diatoms because their rate of uptake of nutrients is much larger than that by cyanobacteria. In nutrient-enriched estuaries located downstream of large dams that preferentially trap the fine sandy sediment, the phytoplankton or diatoms can exhaust the silicate but not nitrogen and phosphorus; when that happens, cyanobacteria take over and harmful algae blooms can result. This situation is becoming common in many estuaries worldwide with a large water transport time scale and a large input of nutrients from sewage and fertilizers.

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EUROPE, LAKES REVIEW

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Introduction

The continent, with offshore islands, including the Faeroes but not Iceland or Svalbard, covers 10,350,000 km². Its eastern border is taken as the Ural Mountains and Ural River. Its longest rivers are the Volga, Danube (Donau), Ural, Dnieper, Don, Pechora, Dniester, Dvina, and Rhine. Iceland (about 100,000 km²) is below included when presenting the European lakes. Europe's northern limit is North Cape (Norway) at 71°10'20"N. and its southern limit is Cape Tarifa (Spain) at 36°01'N, although the southern point of Cyprus (34°30'N) exceeds this. The western limit of the mainland is Cape Roca (Portugal, at 9°30'W); when Ireland is included it is Dunmore Head (Eire, at 10°30'W). The eastern limit is in the farthest north of the Ural mountains (75°30'N).

Europe has some very famous lakes, treasured as beauty spots and honored in song and literature, although most of them are rather small. The majority are associated with the glacial history and deglaciation of the great Fennoscandian ice sheet, and the smaller ones with the glaciers of the Alpine area and the British Isles. Numbers of the lakes have had a compound history: beginning as structural features that were often initiated by strike-slip faulting in the Caledonian or Hercynian orogenies, but later modified by Quaternary glacial activity (e.g., Loch Ness).

Two very large water bodies with many lacustrine characteristics, in this volume are treated as “lakes,” although usually classified as “seas,” are the Black Sea and the Caspian. The latter is bisected by the Europe–Asia boundary, and is treated in the review under “Asia.” In the paleogeographic history of southern Europe and the Mediterranean, the name “Tethys” is intimately associated. It was originally a proto-Mediterranean seaway that divided much of the Earth's continental areas (Gondwanaland and Eurasia) for at least the last 150 million years. The Eurasian landmass to the north, and the African-Arabian-Indian blocks to the south. As these two moved apart, Tethys widened. As they approached briefly from time to time, twin orogenic belts developed parallel to the receding margins. The Viennese professor Leo Kober called this duality the “Zweiseitigkeit der Orogenen.” The French, e.g., Louis Glangeaud, called them the “Orogènes Biliminères.” This was in contrast to the “monoliminarity” of most of the Circum-Pacific tectonism.

From the lakes point of view, there were two very significant events in Tethyan history, which accompanied the progressive left-lateral shifts along the “Tethyan Megashear” zone of Sam Carey, once the leader of Tasmanian geology. First, there was the development

of a string of large interconnected lakes marginal to or in the depressions between the two converging orogenic belts, a zone known to the local geologists as the "Zwischengebirge" (the "betwixt" belt), seen today in the Pannonian Plain of Hungary, the submarine fracture complex of the Aegean, the Black Sea, and the interior plateaus of Anatolia and Iran. Also connected to them were "foredeep" basins in Bavaria, Romania and the Caspian Sea. The entire series was called the "Paratethys." During high eustatic phases the "lakes" became marine gulfs, but during low phases and orogenic compression that isolated the separate basins, gradual hypersalinity developed several times. The paleontologists noted the rapid evolutionary changes (particularly among the mollusca) with each rising salinity. The Black Sea has a history that also goes back into lacustrine phases (the "Euxine Lake"), ranging from fresh to hypersalinity. At times, as a result of freshwater intake, notably through the Volga drainage basin of Central Russia, the level of the Caspian Sea would rise so high that it overtopped the threshold of the Manych Depression, north of the Caucasus and flood into the Black Sea somewhat east of the Sea of Azov.

The other significant event in Tethyan history was the late Miocene closure of the Mediterranean, the so-called "Messinian Event" (6.5–5.3 Myr ago). Closures occurred in the Middle East (at the Aleppo Platform) and between Morocco and Spain (the Betic–Rif loop). Eventually there was a midpoint closure between Tunisia and Sicily. Thick deposits of salt and gypsum mark the evaporating pools of former lakes.

Thus, the present-day lakes of Europe are seen as largely the inheritance of geologic events that began 450–300 Myr ago and reached a crescendo during the last 5 Myr. Over this structural background is followed by a crowning veneer of processes related to the Quaternary glaciations. The finest lakes along the peripheries of the Alps are derived from the mountain and valley glaciers with their distinctive U-shaped valleys, the erosion of which was greatly enhanced by the contrasting uplifts of the Central Alps, and downwarping of their margins, e.g., in the south, Lakes Maggiore, Como, and Garda; in the west and north Geneva (Léman), Neuchatel, Zürich, Constance (Bodensee), and Chiemsee. Two of them are part of major drainage systems (Geneva in the Rhone; Constance in the Rhine). In the Dinaric Belt some major structural features included Lakes Ohrid, Prespa and Scutari.

The Scandinavian ice sheet, though far more extensive, did not inherit such dramatic contrasts, but nevertheless, in many areas, left vast numbers of small and even nameless lakes and depressions down to the level of kettle holes. Its major lakes (Vänern and Vättern) are primarily structural.

Postglacial isostatic recovery from the ice load is particularly noticeable in Scotland and Scandinavia. In places, old peneplains (or etchplains) on Precambrian platforms, e.g., Karelia in eastern Finland and Northwest Russia, are speckled with little depressions and their small

lakes. The broad surfaces of the Russian craton undulate into epeirogenic arches and depressions, the so-called "anteclise" and "syncline" structures, the latter being often the site of multitudes of isolated drainage systems, lakes, and swamps.

Meteorologically, most of Europe is within the trajectories of the prevailing westerlies which bring more or less perennial rains in many latitudes, with the seasonal swing to the north in Scandinavia and to the south in the Mediterranean belt. Oceanicity and continentality play important roles, the latter with increasing importance in eastern Europe, which is particularly characterized by its cold, dry winters. The monsoons of Asia and Central America do not reach Europe, but meridional turbulence often brings scattered summer rains in Southern Europe.

A few lakes in the European–Icelandic framework are directly related to volcanism, either contemporary or recently active in historical or Holocene times. Most famous of course is Vesuvius, near Naples, which erupted in A.D. 79, 1631, and 1944. Mt Etna, in Sicily, is active much of the time, recently in 2002. Stromboli, in the Tyrrhenian Sea was also erupting in 2002. On Iceland many historical eruptions have been recorded during the last 1,000 year, most recently Hecla (2000), Grimsvötn (1998) and Krafla (1984). In the eastern Mediterranean, the most spectacular eruption (and tsunami) was that of Santorini (Thera) in 1628 B.C. which destroyed the mythic city of Atlantis. Its most recent activity was in 1950. Traces of all these early eruptions are found in the bore cores of down-wind lake deposits.

These eruptions are not related in any way to the Circum-Pacific "ring of fire," but those in the Mediterranean belt are linked to motions of the "Tethyan megashear," and those in Iceland are connected with the seafloor spreading axis which bisects the island.

Some interesting crater lakes are found in a series of now-extinct centers, extending to north of Rome (Lago de Bolseno, L. de Trasimeno). The region of the "Puy" (in the Auvergne, southwest of France) is historically of great importance, because here, the geomorphic form of classical volcanic cones, lava streams, and so on was first recognized (1750–1775) by geologists (Guettard, Desmarest) although the activity is now quite extinct. That was in the early nineteenth century and it was several decades before their volcanic origin was universally conceded (Gohau, 1991).

Another area of well-preserved crater lakes ("maars") and clear signs of former volcanic activity is the Eifel district of western Germany. One of the most important eruptions dated by K/Ar methods at the Laacher See (3.3 km²), ash from which is traced in the lake deposits through Germany to Scandinavia. Maars (i.e., steep-sided, round basins, produced by pyroclastic gas eruptions) are also a feature of many Icelandic areas, with small lakes in the craters.

Also, eruptions of widespread significance are those associated with fault activity from Lake Balaton to the Tokaj area of northern Hungary, where the volcanic soils

have been a major factor in the cultivation of some magnificent wine grapes. Lake Balaton itself is the compound product of a complex fracture zone and the blocking of drainage systems by the volcanoes themselves.

Extraterrestrial impacts have created lake-forming depressions in two places in Europe, (a) the Ries crater, 29 km across, in the Swabian Alb of southern Germany and (b) a smaller site in central Sweden.

Coastal lakes in Europe fall into several categories, relating to their tectonic and eustatic histories: (a) Lagoons, with moderately saline to brackish waters, barred by sandy spits, and partly following the course of former river valleys, e.g., “*etangs*” in Southwest France, Northwest Mediterranean (Gulf of Lions), east coast of Corsica, and limans on the Northwest Black Sea. Openings to the sea in the French “*etangs*” are known as “*graus*.” Gravel spits occur in the south of England, e.g., Chesil Bank. (b) Lagoons with sandy barriers but with major fluvial input and permanent inlets from the ocean, e.g., Venice Lagoon, Italy; and at the major river mouths of eastern Spain. (c) Lagoons on major deltas, more or less frequently flooded by fluctuations of the main stream, e.g., the Danube, Rhone, Po. (d) Lagoons in the periphery of former glacial centers, as in the southern Baltic (where the lagoons are called *Haffe*, and the spits are *Nehrungen*, in German). In the UK, examples are the “*Norfolk Broads*.” (e) Lakes inherited from the tunnel valleys and meltwater channels of the last glaciation, e.g., the Limfjorden of northern Denmark. (f) Glacioisostatically uplifted lagoons or arms of the sea (“*loughs*”) in former glacial valleys, e.g., in Northeast Ireland: Lough Neagh; Strangford Lough, Belfast Lough, and Carlingford Lough are all open to the sea; in Scotland, Loch Lomond is 900 m deep, and was the site of the last glacial advance at the end of the Pleistocene.

Reservoirs and man-made lakes in Europe are quite innumerable and go back in time to the “*dew ponds*” of the Bronze Age. Giant barrages and associated lakes are generally absent except for several in Spain and Portugal, and a single major modification at Lake Mjøsa in Norway; also there are major engineering works in the former Soviet regions (Russia, Ukraine, etc.). They include Kuibishevskoe, Rybinskoe, Volgogradskoe, Kremenchugshoe, Tsimlyanskoe, Khakhovskoe, Gorkovskoe, Kamskoe, and many more.

Europe: lake categories

Epeirogenic basins, plateaus, and plains
(syncline, etc.)

The position of the lakes below are shown in (Figure 1), unless otherwise is stated.

1. *Lake Ladoga*, with 17,700 km² (6,835 square miles) is the largest lake in Europe. It is located northeast of St. Petersburg in Karelia (northwest Russia). It is fed by about 70 rivers, most important being the Svir River from Lake Onega (see below) and the Vuoksi River from Lake Saimaa. Its entire drainage basin is 258,000 km². Its outlet is through the Neva River into

the Gulf of Finland. It is linked by an extensive canal system with the Gulf of Finland, the White Sea and the Volga basin. Heavy rains in June and September cause the lake level to rise notably at those seasons. It is frozen in winter. Geologically its basin is tilted to the east and south, so that these shores are low and sandy, while northwestern shores are high and rocky, reflecting the glacioisostatic recovery of Fennoscandia.

2. *Lake Onega* (Onezhskoye Ozero), the second largest lake in Europe, is 9,630 km² (3,720 square miles), being located 130 km northeast of Lake Ladoga, which is fed by its overflow through the Svir River. Its surface elevation averages 33 m (108 ft), fed by a number of small streams. Its northwest shore is deeply indented by postglacial drainage channels. For a short period at the end of the Pleistocene, there was a continuous seaway from the White Sea to the Baltic. Maximum depth today is 138 m. It was connected by canals in 1852, and seagoing ships from the Russian Arctic can reach the Gulf of Finland, and through this “*Mariinsk Canal*” system, also the Caspian and Black Seas, except during the winter freeze-up (November to May).
3. *Lake Peipsi* (Chudskoye Ozero in Russian), forming part of the border between Estonia and northwest Russia. An extension in the south is Lake Pskov (710 km²). The combined area is 3,550 km² (1,370 cubic miles). The entire area to the east is low and swampy, but dry and undulating to the west. Its outlet is the Narva, flowing into the Gulf of Finland. Fed from the west by the Ema and from the south by the Velikaya. The whole drainage basin is 44,200 km².
4. *Ozero Ilman*, a shallow lake in Novgorod Oblast, 160 km south-southeast of St. Petersburg.

It varies in size with the seasons from 1,100 to 2,200 km² (425–850 square miles). It is fed by the Lovat and Msta rivers, and its outlet is the Volkhov which drains into Lake Ladoga. The entire area is low and swampy, extending over 66,300 km².

5. *Finland Lake District* occupies the eastern part of Finland (Keski-Suomi, Kupio, Pohjois-Karjala and Mikkeli), lying N of Helsinki, where a large number of interconnected water bodies trending roughly the northwest–southeast area relic of the last glacial stage of the Pleistocene. The general elevation is less than 100 m. Farther north, in Finnish Lapland, there are additional lakes and swampy areas that connect to the Barents Sea (Varangerfjord).
6. *Bug–Pripiet Marshes*, situated in eastern Poland, southern Belarus and western Ukraine, is a very extensive area of lakes and interconnecting rivers that eventually drain into the Vistula and the Baltic. The Polish sector is reserved as national parks (Poleski, etc.). (The Bug is sometimes called the “*Western Bug*” to distinguish it from the “*Southern Bug*,” or ancient Hypanis, that drains into the Dnieper and Black Sea.) A canal joins the Bug and the Pripiet and thence to the Dnieper. It rises in the Volyno-Podolsk uplands



Europe, Lakes Review, Figure 1 Position of European lakes described in the text.

(steppes), east of Lvov, an area of Precambrian basement rocks. The rivers are generally frozen from December to March.

7. *Masurian Lakes* (Jezioro Sniardwy, etc.), a string of small lakes in northeast Poland to the borders of Lithuania and to south of the Kalingrad Oblast (Russia; former East Prussia). The central area is designated as the Mazurski National Park. Very picturesque, the lakes, being a product of ice-age tunnel valleys, are mostly long and narrow. The largest is Sniardwy (122 km²) and the next is Mamry (104 km²). The surrounding forests are primeval and well preserved, together with their varied wildlife.
8. *Sea of Azov* (Azovskoye More) a generally shallow body of water (67,760 km², 14,517 square miles), situated in southern Russia between the southern Ukraine and the mouth of the Don River (Gulf of Tagenrog). It is connected to the Black Sea by the Kerch Strait.

It had been commercially exploited by the ancient Greeks (it was called "*Palus Maeotis*") who had established several small colonies there. Its sandy shores were very favorable for shallow-draft boats. There is a prominent sandspit, the "Tongue of Arabat" (*Arabatskaye Strelka* in Russian), some 230 km long, that projects from the west side. On the southeastern margin, there are a number of coastal lagoons. Its depth is everywhere less than 100 m and during ice-age desiccation it dried out several times.

Structural depressions (Graben, etc.)

1. *Lake Vänern*, the largest lake in Sweden, a product of block faulting in the Precambrian basement rocks, but modified by Pleistocene glacial action. It is 5,550 km² (2,100 square miles), draining southwest into the Göte River, which flows to Göteborg and the North Sea. Many rivers drain into it, notably the Klar which rises in Norway. Its drainage basin is

- 46,800 km². Canals connect Göteborg to Stockholm via Lakes Vänern and Vättern.
2. *Lake Vättern*, second largest of Sweden's lakes, with 1,900 km² (730 square miles). Its drainage basin is only 6,360 km² and thus much less than for Lake Vänern. Its structural form is a graben in the Precambrian basement, but its eastern margin is marked in part by early Paleozoic limestones. Glacial excavation further deepened the depression to 61 m below sea level.
 3. *Lake Mälaren*, a third structural depression in central Sweden, 1,140 km² (440 square miles), distinctive because it was formerly an arm of the sea. Because of glacioisostatic uplift (here, about 5 mm/year) the Earth's crust has risen so that it is now cut off (since A.D. 1200) at the city of Stockholm. About 1,000 year ago, Vikings from settlements along the lake could undertake trading (or looting) voyages to western Europe or using the rivers of eastern Europe could reach the Black Sea and eventually Baghdad.
 4. *Loch Morar*, the deepest glacial lake in Scotland (308 m, 1,017 ft), on the western coast, west of Inverness. Other glacial lakes are numerous, and oriented more or less radially because of the centralized Scottish ice cap, but most are modified by the structural foundations, the most extreme example being Loch Ness.
 5. *Loch Ness*, in Scotland, is almost unique in that it marks a major strike-slip fault zone (trending northeast–southwest) in a sinistral, left lateral sense. Its form was slightly modified by glacial erosion. It is 37 km (23 miles) long but only 1–2 km wide. It is 227 m (751 ft) deep, 57 km² (22 square miles). It is only the second deepest in Scotland, after Loch Morar (308 m, 1,017 ft).
 6. *Lake Mjøsa*, the largest lake in Norway, a glacially modified structural depression that is linked with other fracture zones to the Rhine Graben and others to the Rhone valley. Located in southeast Norway, in Oppland and Hedmark counties, north of Oslo, it covers 368 km² (142 square miles), and 99 km (62 miles) long. Other glacial lakes in Norway are more or less radially directed reflecting the maximum ice thickness over western Scandinavia, but modified by the structural foundations of the post-Caledonian fractures.
- Intermontane and intramontane basins**
- In the Tethyan orogenic belt, between the N-thrusted and the S-thrusted folded zones, there is a zone of intermontane basins, e.g., within the Pannonian basin, and in the inner parts of the twin orogenic belts which are strictly intramontane.
1. *Black Sea (Chernoya More: Russ.; Pontus Euxinus: Latin)*. It covers about 446,000 km² (180,000 square miles). This is the largest and most complex of the “Para-tethys” basins, and also the deepest. It has been in existence since the Miocene, and its salinity has fluctuated from nearly fresh to hypersaline, reflecting the patterns of the changing climates and the amplitudes of the intake discharges. The present waters are saturated with H₂S and lethal to most forms of life below a depth of about 90 m. Bordered to the north by the Crimea and western Caucasus, and to the south by the Pontic Ranges of Anatolia, it has only one outlet, the Bosphorus (to the Sea of Marmara and the Mediterranean). It is fed by many rivers, notably the Danube, Dniester, Bug (Southern), Dnieper, and Kuban (from Europe), and the Kizil Irmak and Sakarya (from Anatolia). At the Kerch Strait it is linked to the Sea of Azov and the river Don. From time to time, the Caspian Sea has overflowed into it via the Manych Depression north of the Caucasus, and generally out of phase with the periodic shrinking of the Black Sea, when a “Euxine Lake” is created.
 2. *Balaton* (Plattensee, in German), with about 600 km² (232 square miles), it is the largest lake in central Europe and occupies a fracture zone in the northeast–southwest structural trends of the Pannonian Basin of Hungary. Important volcanic cones (extinct) mark its northern shores. Its southern shore is low and sandy. Its maximum depth is 115 m. Its major feeder is the Zala River, and its outlet at Siofok to the Sio River eventually reaches the Danube.
 3. *Neusiedlersee* (Hungarian: Fertő-tó), is a shallow lake on the northwest borders of Hungary and southeast Austria, covering 318 km² (123 square miles). Its area is a National Park.
 4. *Lake Scutari* (Ligen-i-Shkodres in Albanian; ancient: *Palus Labeatis*) is located on the border between Montenegro (Serbia) and Albania, in a geological depression (graben) that is separated from but parallel the Adriatic. It covers 370 km² (143 square miles). It is fed from the north by the Morača River, and drains to the south into the Bunë and the Mediterranean.
 5. *Lake Ohrid (Lichnides of classical times)* is located partly in Albania and partly in Macedonia. It is the remnant of a large number of Miocene and Pliocene lakes that developed during late Neogene uplift in the Dinaride belt but were gradually filled in or bypassed. Lake Ohrid (32 km², 20 square miles) is 40 km long, picturesquely surrounded by steep mountains, and notable for retaining some of its original distinctive Neogene faunas. It is comparable to Lakes Prespa, Arissa and some smaller ones. Lake Ohrid is drained by the Crni Drim and its several lakes, eventually reaching the Mediterranean.
 6. *Lake Prespa* is situated 10 km southeast of Lake Ohrid to which it is linked by an underground karst channel, but has no surface outlet. It has a small appendage to the south, which makes a total length of 37 km (23 miles). The international borders of Albania, Macedonia, and Greece meet here.

Glacial troughs

1. *Lake Maggiore* (ancient: *Verbanus Lacus*) in northern Italy and southern Switzerland, a classical glaciated valley from the southern (Lepontine) Alps, is 210 km² (81 square miles), only 3 km (2 miles) wide but 64 km (40 miles) long. It is 370 m (1,220 ft) deep and is traversed by the Ticino River. Within it, there are four picturesque islets (the Borromean Is.).
2. *Lake Como* (ancient: *Comum Lake*) situated east of Lake Maggiore in the Lombardy province of North Italy. It is traversed by the Adde River. The lake is 130 km² (50 square miles), 60 km long and only 5 km across. Slightly to the west is a smaller body the *Lake of Lugano* (*Lacus Ceresius*, in Latin) about 49 km² (19 square miles), and 286 m (945 ft) deep.
3. *Lake Garda* (ancient: *Lacus Benacus*) is located in eastern Lombardy in North Italy, bordering Veneto. It is 52 km (30 miles) long, and up to 17 km across, spanning 370 km² (143 square miles). It drains to the south into the Mincio River and eventually the Po and the Adriatic.
4. *Lake of Geneva* (*Léman* in French; ancient: *Lake Lemanus*), situated partly in Switzerland, partly in France. It covers 580 km² (224 square miles), 75 km long and up to 15 km across. From east to west it is traversed by the River Rhone which rises in the Bernese Alps and discharges into the Mediterranean. It was here that the first optical effects of warming air over cooler lake water (mirage) were observed and recorded. Also observed here were the submarine landslides caused by Rhone flooding at the eastern end. The lake is also notable for its seiche response to sudden wind reversals.
5. *Lake of Neuchatel* is situated in northwest Switzerland on the edge of the Jura mountain belt. It is 135 km² (84 square miles) in area, and 150 m (502 ft) deep. Closely linked to it east-northeast is a smaller body, the Bielersee in the Canton Bern, which is drained by the Aare River, a tributary of the Rhone.
6. *Lake of Zürich*, the largest of a cluster of glacial lakes in east-central Switzerland, 88 km² (34 square miles), 40 km (25 miles) long and narrow, 1,538 m (469 ft) deep. Others in this group include the Wallensee (24 km², 9 square miles) and Zügersee (39 km², 15 square miles). Wallensee is linked by the Linth Canal to the Lake of Zürich.
7. *Lake of Lucerne* (*Vierwaldstättersee* in German) (in between Lake Neuchatel and Lake Zurich - not shown in Figure 1) has a star shape with branches into four cantons: Schwyz, Uri, Unterwalden and Lucerne. It covers 114 km² (44 square miles), is 38 km (24 miles) long, but only 10 km wide. Its main input is from the river Reuss, entering in the south at Flüellen, and leaves at the city of Lucerne. It is famous in the history of geology as the place where strong overfolds and faults were first recognized in the exceptionally clear and continuous outcrops along the sides of the lake. Also in human history (twelfth century) for the site of the alleged marksmanship of William Tell (at Altdorf).
8. *Lake Constance* (*Bodensee* in German; *Brigantinus Lacus* in Latin), located on the eastern border of Switzerland with Germany and (in a short sector) with Austria, it is traversed by the river Rhine, which enters in the southeast and leaves through another small lake, the Zellersee, in the west-northwest. It is 554 km² (210 square miles), 74 km (46 miles) long, up to 13 km (8 miles) across, and has a maximum depth of 250 m (827 ft). The waters have a seiche response to sharp change of wind direction. Stone-Age people had lake dwellings (about 2700 B.C.) along the shore when the lake level was lower than today.
9. *Ammersee* (west of Chiemsee - not shown in Figure 1) is one of a series of moraine-dammed lakes that mark the Bavarian foothills of the Eastern Alps. It is 48 km² in area, and located 34 km (21 miles) west-northwest of Munich. Dated moraines match each of the major glacial advances in the Alps.
10. *Chiemsee*, the largest lake in Bavaria and one of the series that occupy the foothills of the Eastern Alps. It is 64 km (40 miles) east-southeast of Munich. It is 80 km² (31 square miles) at 514 m (1,699 ft) above sea level. Its outlet through the Alz joins to the Inn, and eventually the Danube.
11. *Attersee* - not shown in Figure 1 (or *Kammersee*), in upper Austria, 55 km east of Salzburg. It continues the series of glacially formed lakes that span southern Bavaria. It is 45 km² (17 square miles) in area.
12. *Traunsee* (*Gmundnersee*), in upper Austria, one of a series that mark the Salzkammergut of the Eastern Alps, 25 km² (9 square miles) in area. They are notable for their picturesque settings.
13. *Hallstättersee* (not shown in Figure 1) is one of the Salzkammergut lakes, only 8 km² (3 miles), but famous for its early Iron-Age culture (dated about 900 B.C.), with its multiple graves and art objects, discovered in 1846–1899.
14. *English Glacial Lakes*, notably *Lake Windermere*, 32 km (10 miles) long and the largest in England. Windermere is the site of paleomagnetic measurements going back over 10,000 year. The “Lake District” is a star-shaped cluster of 17 major lakes, designated as a national park, and made famous particularly by the poet William Wordsworth (1770–1850), who lived at Grassmere. Many of the lakes are known as “meres” or “waters” while the small, up-valley ones are “tarns.”
15. *Scottish Glacial Lakes*, notably *Loch Lomond*, 70 km² (27 square miles), the largest lake in Scotland, typically long and narrow (38 km, 24 miles long), and reaching 180 m below sea level. Most of the other glacial lakes of Scotland are dominated by structural

foundations (see under section Structural depressions [Graben, etc.]). The “Loch Lomond Readvance” was a brief but distinctive reversal of the last general deglaciation, at the time of the “Younger Dryas” (dated about 10,500 year BP).

16. *Glen Roy* (not shown in Figure 1), site of a former glacial lake, situated to the southeast of Loch Ness, that was once blocked by the ice. As the glacier receded in steps, each was marked by an erosion bench, probably amplified by abrasion caused by ice on the lake, resulting in a series as a succession of “Parallel Roads.” For many years, the “Parallel Roads of Glen Roy” were an enigma until the glacial theory became thoroughly developed.
17. *Icelandic glacial Lakes*. With its geotectonic situation on top of the mid-Atlantic seafloor spreading zone, Iceland can be expected to display a wide variety of lakes, and because of its mean latitude, 65°N latitude, most of them are related to glaciation. One exception is Öskjuvatn in the Nordurland Eystra division, a crater lake, close to the northeast–southwest spreading zone. Most of the overdeepened glacial troughs are occupied by long, narrow lakes, e.g., Lagerfljót (Austurland). Many are irregular, moraine-dammed, e.g., Myvatn (Nordurland Eystra), Pingvallavatn (Sudurland), and Blöndulón (Nordurland Vestra). Around the coast, there are many blocked estuaries in old glacial troughs, as well as barred embayments, e.g., Leirur and Hornafjörður. There are also some broad areas in the interior marked by numerous thermokarst lakes and swamps, e.g., Arnarvatnsheidi.

Glacio-isostatic lakes

1. *Torneträsk*, in the Swedish far north (Lapland), which is long and narrow, oriented west-northwest–east-southeast. It is cut off by the isostatic uplift from the inner limit of the Narvik Fjord of Norway. The area is a National Park, with a scientific research station at Abisko. The railway from the iron mines at Kiruna to Narvik follows the southern border of the lake. The lake’s outlet is now to the east and forms the eastern border of Sweden with Finland before discharging into the Gulf of Bothnia, and thus the Baltic.
2. *Akkajaure*, situated farther south, also near the Norway–Sweden boundary, this lake eventually drains into the Luleälven to debouch into the Gulf of Bothnia at Lulea. It is likewise a National Park area. Numerous other reversal drainage systems mark the border areas to the south, e.g., the Angermanälven and Indalsälven (that debouches near Sundsvall). These valleys were former lakes that became important in the Quaternary world history because of their varved clays in the old lake deposits that enabled Baron E. De Geer (in 1910) to calculate the absolute ages of the Holocene. Recently, the deposits were systematically resampled and the original timetable (with small revisions) was confirmed.

3. *Enarejärvi*, an important isostatic lake about 75 km long in Finnish Lapland, situated about 150 km southwest of Kirkenes on the Varanger Fjord, an inlet from the Barents Sea (part of the Arctic Ocean). The isostatic uplift along the coast and climatic fluctuations here can be measured by the cyclical steps of the uplifted beachridges. The emergence began about 12,000–13,000 year ago. The lake has no outlet but is surrounded by peat swamps that extend about 500 km southward to central Finland (see Oulujärvi).
4. *Pya-Ozero*, another isostatic lake, located about 80 km southwest of Murmansk in the northwestern corner of Russia. It is connected by the Tuloma River to the Kola River near Murmansk. The Kola River drains a number of similar lakes near Apatity. To the east of here is the Kola Peninsula which is rimmed by uplift terraces but on a reduced scale compared with those of the Varanger Fjord.
5. *Oulujärvi*, Finland’s fourth largest lake, is about 50 km across, 1,041 km² (387 square miles), 160 m above sea level, and located about 75 km southeast of Oulu on the Gulf of Bothnia. It is drained there by the Oulujoki River. From here northward for 800 km to the region of Inarijärvi, there is a continuous belt of peat swamps with scattered lakes (*jaure*, and *javvre* mean “lake” in Lappish) which are interconnected through Kemijärvi Lake and the Kemijoki River to the northern end of the Gulf of Bothnia. The entire gulf area is still rising (at several mm/year) following the retreat of the Fennoscandian ice sheet. The retreating sea levels are marked by beach ridges separated by low, swampy areas.
6. *Lake Päijänne* (not shown in Figure 1) is in south-central Finland covering 1,506 km² (560 square miles), and 75 m above sea level. Although its bedrock is Precambrian granite-gneiss, there is superficial morainic material which affords material for some sandy beaches. In the summer season, when the lake is not frozen, it is linked by with nearby lakes by an extensive canal network for the logging industry.

Karst lakes, and others of lithic controls (these lakes are not shown in Figure 1)

Karst lakes are, by definition, restricted to limestone terrain and are generally very small and associated with cryptorheic drainage systems. In the European area, they are mostly found in the Mesozoic deposits of the old Tethyan seaway, notably in the Dinaric belt of Croatia, Slovenia, Bosnia, Albania, and Greece.

1. *Plitvice Lakes*, located in Croatia, 100 km (65 miles) south-southwest of Zagreb. There are 16 of these lakes that drain eventually into the Kupa River that joins the Sava below Zagreb. The area is preserved as a national treasure. The world’s classical karst areas (“kras” is the word in Croatian) are located in this region.
2. *Brenne and Sologne Lakes*, on the northern margin of the French Massif Central, are not karstic but are

related to the detrital granitic sands transported to the north, and produce a “hydromorphological” unit that is studded with small lakes, a national park.

Volcanic lakes (these lakes are not shown in Figure 1)

Crater lakes (“Maaren” in German) are best known in the Eifel district of Germany and in the Auvergne of the French “Midi” (e.g., the “Puys,” in French). They are extremely small but are geologically most interesting.

1. *Laachersee*, in the Eifel 25 km northwest of Koblenz, which is the site of a major eruption in the early Holocene that spread identifiable ash over much of northwestern Europe. (The glass shards are uniquely correlated with this particular event.)
2. *Monts Doré*, in the French Auvergne, designated as the “Parc Naturel Régional des Volcans d’Auvergne,” this was an important area in the history of geology, because of the cones and their lavas as being first recognized as volcanic, although totally extinct.

Coastal lagoons (these lakes are not shown in Figure 1)

1. *Etangs* of southwest France. Barred by littoral dunes in the Landes area, these include Etang de Biscarosse to E. de Carcans, situated respectively southwest and northwest of Bordeaux. Farther north is one at Les Sables d’Olonne in the Vendée and the Marais Breton, south of the River Loire.
2. *Etangs* of the Golfe du Lion of southern France (Languedoc-Roussillon). These include the Etang de Canet, Leucate, Lapalme, and Ayralla. Radiocarbon dates show their progressive evolution with successive Holocene beachridges building out seaward.
3. *Albufera*, on the Spanish Mediterranean coast just south of Valencia, which was a broad embayment cut off by a major baymouth bar. A similar example south of Alicante is the *Laguna Salada* and an incompletely enclosed embayment, Mar Menor Los Alcázares.
4. *Doñana*, marking the mouth of the Guadalquivir River and a wide swampy area, the Marismas, is protected as a National Park.
5. *Algarve lagoons* of southern Portugal, a national park, with some openings in the barrier islands (Cabo de Santa Maria).
6. *Lagoa de Santo Andre* (and others) situated on the southwest coast of Portugal.
7. *Rio de Avoiro*, on the west coast of Portugal between Coimbra and Oporto, a many fingered embayment, cut off by a long barrier island.
8. *Etang d’Urbino*, on the east coast of Corsica and several smaller ones, Biguglic, Diana, and Palo. All are related to the extreme periglacial activity in the mountains and the fluvial transportation of frost debris to the coast, thus providing an abundant supply of sand for the baymouth bar building.
9. *Stagno dè Cabras*, also *Stagna di Santa Giusta*, with multiple baymouth bars, on the west coast of Sardinia, northwest of Cagliari.
10. *Laguna di Orbetello*, a classic site of a triple tombolo on the northwest coast of Italy about 100 km northwest of Rome. Dating of the tombolo spits is aided by the presence of fish tanks from the classical (Roman) period.
11. *Lago de Massacinerò*, situated 15 km north of Pisa on the Italian west coast, the bayhead bars being fed by the abundant sediment brought down by the Arno.
12. *Laguna Veneta*, situated at the head of the Adriatic, north of the Po delta, and that of the Adige. The city of Venice is located on an island in the lagoon, which has several natural openings. A smaller but rather similar lagoon (*Laguna di Marano*) is located about 45 km to the east. And another, *Valli di Comacchio*, is situated to the south, about 15 km north of Ravenna.
13. *Lago di Lesino* and *Lago di Varano* are situated side by side on the N border of the Gargano Peninsula. Both are contained by regular baymouth bars.
14. *Lago di Fogliano*, *Caprolace* and *Sabandia* are located in a line NW of Monte Circeo, 90 km south-east of Rome, and site of a famous Neanderthal cave. The pre-Last Glacial sea level has left a distinctive notch in the cave.
15. *Limnithalassa Mesolongiu*, is situated on the Gulf of Patras in western Greece, just east of the Achelooos delta. This river drains a number of structural-depression lakes in the interior. The *Limnithalassa* includes a large number of islets but also wide openings to the sea (Ionian Sea).
16. *Limans of Danube Delta* (*Lacul Razim* etc.), the south side being in Romania and the northern side in Ukraine (Odessa Oblast), where the classical limans were first described on the lower Dniester, the southern Bug and other rivers. The limans are a series of lagoons separated by barrier islands in succession, apparently repeated due to climatic fluctuations and associated submergence.
17. *Zuider Zee*. Prior to the thirteenth century there were a series of lakes and swamps in the IJssel valley of east-central part of the Netherlands, but in the early Middle Ages the barrier to the Waddenzee (and North Sea) was breached by storms and eustatic rise. The *Zuider Zee* (“South sea”) then became a reality, as an oceanic inlet. In the twentieth century a new North Sea dike re-created the Isselmeer, but only briefly, as segments became cut off by polders.
18. *Norfolk Broads*. Part of eastern Norfolk became drowned by eustatic rise during the middle Holocene, but crustal movement has subsequently provided uplift and isolation of much of the area into a succession of lagoons, which are nevertheless partly tidal.

19. *Jadebusen* and other embayments in northern Germany (Friesland), have undergone somewhat similar histories of evolution from lagoons or lakes to marine gulfs.
20. *Ringkøbing Fjord* on the west coast of Denmark is a regular barred embayment about 30 km long. (In spite of its name, it is totally unrelated to the normal geological landform "Fjord.") Its barrier is known as the "Holmsland Klit." Numerous small lagoons occur farther north, including "Nisum Fjord."
21. *Limfjorden*. The "Nisum Bredning" provides access to the giant "Limfjorden" that separates the whole of northern Denmark from the North Sea (Skagerrak). The origin of the Limfjorden appears to be the isostatic uplift from deglaciation associated with crustal tilting to the south, that is superimposed by the oscillatory ripple effect created by the Holocene eustatic fluctuations. (The Limfjorden phenomenon appears to be almost replicated in Northeast Germany by the Boddensee complex, see below.)
22. *Boddensee, Hiddensee, Jasmunder Bodden*, and related embayments near Rügen in Northeast Germany, facing the Baltic Sea, have undergone alternate lacustrine and marine inundation histories during the Holocene. All are linked to the Baltic by inland channels, and only the "Kleine Jasmund" is isolated. Today, these are national park systems, the Boddenlandschaft and Rügen-Jasmund, which are followed to the southeast by the Greifswalder Bodden (open to the sea and linked to the others by the Stralsund channel) and the Insel Usedom (which is not). The interplay here between Holocene fluctuating eustasy and the ripple effect of the postglacial isostatic movements attracted particular attention from the Shorelines Commission of the International Union of Quaternary Studies in the period 1960–1970.
23. *Oderhaff Haffküste/Zalew Szczeci/Eski* is an extensive lagoon near the mouth of the Oder/Odra River which here forms the boundary between Germany and Poland (and hence the multiple names). Postglacial isostatic uplift and strong longshore sediment transport combine to build a massive barrier at the mouth of this major river. Smaller lagoons are created farther east (Jamno, Bukowo, Kopan). Some 50–100 km south of the coast, there is a broad arc of uplift that from the region of Lübeck in the west to Gdansk in the east, that has blocked river valleys to create numerous tectonic-barrier lakes, known as the "Pomeranian Lake Belt" (Podjezierze Pomorskie).
24. *Wisłany (Vistula) Lagoon*, in the east part of the Gulf of Gdansk is a classic barred embayment, the early German works on the subject refer to this type of bar as a "Nehrung" ("Mierzeje" in Polish). In the western part of the Gulf a new spit, the "Promontory of Hel," named for the settlement "Hel" at its SE tip. The bar has been nourished by sediments carried down by Poland's largest river, the Vistula (*Wisła* in Polish, *Weichsel* in German). To confuse matters, the eastern part of the Wisłany Lagoon, formerly part of East Prussia, is now a segment of the Russian Federation, and has a Russian name, the Kaliningradskiy Zalif.
25. *Courland Lagoon* (Kurische Haff, in German) lies partly in the Kaliningrad province (Russia) and partly in the southwest corner of Lithuania, where it is protected as a national park. Its baymouth bar ("Nehrung") is 100 km long, from Zelenogradsk in the south to Klaipeda in the north. Farther north on the Baltic coast, there are some smaller lagoons, in Latvia and the Gulf of Riga.

Reservoirs and man-made lakes

Europe is probably the oldest reservoir-building society, going back to the times of Greek and Roman urbanization. Rainfall collection on a house-by-house basis probably extends several millennia earlier, but a plentiful supply of water only became a social necessity when houses were built close together and required some sort of hygienic waste disposal. Deep conduits have been found by archeologists working on the foundations of Jerusalem, and water was needed for flushing them. Multi-seat marble toilet services were provided in the Greco-Roman colonies of North Africa and are still freshly preserved because of burial for many centuries under Saharan sands.

Reservoir and canal construction for irrigation purposes were probably initiated in Babylon (modern Iraq) and other communities along the two great rivers, the Tigris and Euphrates, of Mesopotamia, as early as 5000 B.C. The seasons are very contrasted and the floodwaters of the two great rivers would demand some sort of human control. Direct evidence is lacking, but probably began with the simplest forms of earthen channels that leave no archaeological evidence. The same seasonality is also a feature of the Nile and in pharaonic times (probably even the First Kingdom) the social organization was in place for irrigation management.

In Europe, great rivers with their seasonal flooding exist in the case of the Danube, the Rhine, the Rhone, and a few others, but early social organization for the utilization of their waters appears to have been lacking. It was only with the development of centers of urbanization associated with the imperial organization of Rome, with road building and city planning, that systematic hydrologic services were seen as a necessity. It seems to be a sad fact that only the discipline of that Roman power could maintain these services. Many fall into disrepair. Others were simply neglected by the scattered tribes that followed the A.D. 400 breakdown. It is interesting that organized Christian religiosity was a curious factor in the moral rejection of communal bathing and the general disappearance of public bath houses.

With the intellectual renaissance that followed the reign of Queen Elizabeth I and her scientific advisors, a gradual

reassertion of the importance of hydrology began. It was only in the reign of Queen Victoria that the first operating water-closet was introduced, and thus the beginning of the end of the “great unwashed.”

Cross-references

Balaton Lake in Hungary
 Classification of Lakes from Origin Processes
 Finnish Lakes
 Geneva Lake
 Ladoga Lake and Onego Lake (Lakes Ladozhskoye and Onezhskoye)
 Lough
 Peipsi Lake in Estonia/Russia
 Russian Lakes
 Sweden's Great Lakes
 Võrtsjärv Lake in Estonia

EUTROPHICATION IN FRESH WATERS: AN INTERNATIONAL REVIEW

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Definition and Introduction

Aquatic eutrophication: from the Greek “eutrophia”, meaning “well nourish”.

Eutrophication is defined by the European Commission, in the Urban Waste Water Treatment Directive as:

The enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms and the quality of the water concerned.

In a foreword to its report on Water Quality: The Impact of Eutrophication, the United Nations Environment Programme (UNEP) notes that:

Eutrophication is one of the most widespread environmental problems of inland waters, and is their unnatural enrichment with two plant nutrients, phosphorus and nitrogen. Such changes can destroy wildlife habitats and interfere with a range of water uses from recreation to the production of drinking water.

Origin of the concept of eutrophication in fresh waters

The idea of eutrophication began with limnologists. Early in the twentieth century, northern European limnologists distinguished *oligotrophic* from *eutrophic* lakes. The former were nutrient-poor, the latter nutrient-rich.

Hutchinson (1973) reviewed the early development of ideas about eutrophication. In 1907, C.A. Weber invented the (German adjectival) terms *eutrophe*, *mesotrophe* and *oligotrophe* to describe different states of the flora in German peat bogs as the bogs changed with time through accumulating material. Hutchinson wrote:

At first the bog vegetation was what Weber called eutraphent, requiring high concentrations of essential elements in the soil

solution; at the end of the process (as the bog level built up above its surroundings, and became more leached) an *oligotraphent* flora covered the bog, composed of species tolerating very low nutrient concentrations.

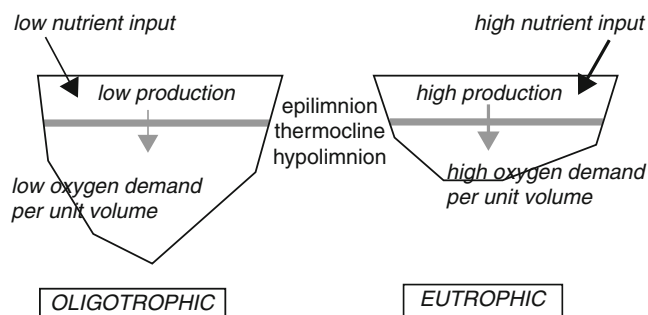
Naumann (1919) used Weber's terms in a discussion of phytoplankton in Swedish lakes. He began by considering water types, which might be *oligotrophic*, *mesotrophic* or *eutrophic* depending on their content of mineral nutrients – as water might be labeled fresh, brackish, or marine depending on its salt content. However, chemical techniques available to Naumann did not allow nutrient concentrations to be reliably measured, and so he redefined the categories to apply to lakes, according to their appearance in summer and the most abundant types of phytoplankton. Other studies of European lakes supported the idea about distinctive floras, with the thick-walled green algae called desmids seen as the characteristic phytoplankters of the oligotrophic lakes of mountainous regions, and diatoms and blue-green bacteria seen as characteristic of eutrophic lowland lakes.

Stratification

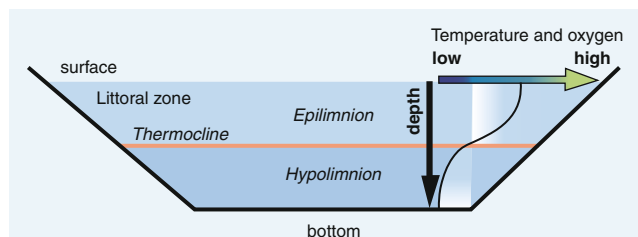
Using data from North America and Germany, Thiennemann (1918) showed that some stratified lakes experienced severe oxygen depletion in the *hypolimnion* (the water beneath the seasonal *thermocline*). Adding these findings to Naumann's definitions gave the *oligotrophic–eutrophic paradigm* (Figure 1).

At certain times, lakes may form a *thermocline* some meters below the surface (Figure 2). In the thermocline, the temperature declines several degrees over a few meters and divides the lake into two zones an upper warmer one, the *epilimnion*, and a lower colder one, the *hypolimnion*. Lakes in temperate regions usually have depths of 5–10 m or more. Such lakes typically form a thermocline during the summer time and stratify. Shallow tropical lakes can also stratify, but stratification can be broken down by strong winds.

A thermocline prevents the upper and lower layers of the lake from mixing. The result is a change in vertical oxygen concentrations, where concentration is high in the upper layer or epilimnion and very low in the lower layer or hypolimnion. The low oxygen concentration may degrade water quality downstream of the lake or



Eutrophication in Fresh Waters: An International Review, Figure 1 Thiennemann's *oligotrophic–eutrophic paradigm*.



Eutrophication in Fresh Waters: An International Review,
Figure 2 Thermocline and the relationship between temperature, oxygen and depth in lakes within temperate regions.

reservoir, particularly downstream of reservoirs with short retention times.

Stratification and mixing were the subject of research by Lack and Lund based on observations in the small lake Blelham Tarn, in the English Lake District. They describe the dynamics of stratification in three stages:

- The surface-mixed layer or epilimnion
 Absorption of the sun's heat in near-surface waters creates stability because warm water is buoyant. Heat is lost from water to air directly and through evaporation of water – this cools the surface layer and also mixes it convectively. Mixing is also caused by wind. The surface mixed layer first forms in spring, when the stabilizing effects of heating exceed the mixing effects of stirring by wind and night-time cooling.
- The (seasonal) thermocline and internal mixing
 The seasonal thermocline is the upward retreat of the surface-mixed layer, at its most developed in late summer. Weak internal mixing in the thermocline results from internal waves which break in the thermocline and along the lake walls. This mixing is too weak to break down the thermocline during summer but may slowly transfer deep water nutrients into it. The hypolimnion is the bottom water of a lake, actually the lower part of the thermocline.
- Surface cooling and the autumn overturn
 During autumn the epilimnion loses heat and cools, and gradually deepens, entraining deeper water from the thermocline and then the hypolimnion, until eventually the entire water column is mixed.

Production

By the 1960s, limnologists had developed reliable and sensitive methods for measuring the concentrations of chlorophyll and nutrients in lakes and were beginning to collect time series showing changes during the year. The simplest analysis of these data involves plotting summer chlorophyll on winter-dissolved nutrient, either from one lake in many years, or from many lakes. The yield is the ratio of (summer) chlorophyll to initial (winter) nutrient, and the rationale is that phytoplankton is negligible in winter, when nutrients are abundant; the growth of phytoplankton during the spring converts all available nutrients into phytoplankton.

Some workers, however, plotted chlorophyll averaged over the year against "mean total nutrient". In the case of P, the latter includes all forms of the element in the water column. In winter it is mostly present as dissolved phosphate, but, by summer, most of it is contained in organisms, detritus, or dissolved organic P. In the case of N, the total includes particulate organic N, dissolved organic N, and the dissolved inorganic compounds nitrate, nitrite, and ammonium; but not dissolved nitrogen gas, which is not usable by most plants.

The total nutrient approach can be seen as giving improved prediction of initial nutrient on the basis of all-year data, if it is assumed that re-mineralization of organic forms of a nutrient will contribute to next winter's dissolved inorganic nutrient. It also allows for the uptake of dissolved organic nutrients by some phytoplankton. The comparison of winter nutrient with summer chlorophyll is conceptually simpler. In either case, the existence of a statistically significant correlation between chlorophyll and nutrient has generally been taken as implying nutrient limitation of biomass, with the slope of a regression line giving the yield ratio. In studies carried out in the "Experimental Lakes Area" of Ontario a group of lakes was set aside to observe the effects of adding nitrate and phosphate (Johnson and Vallentyne, 1971; Schindler et al., 1971, 1978).

Schindler (1977) concluded that

Evidence has mounted for an astonishingly precise relationship between the concentration of total phosphorus and the standing crop of phytoplankton in a wide variety of lakes, including many in which low nitrogen-to-phosphorus ratios should favor limitation by nitrogen.

Schindler also demonstrated that knowledge of total P also explains much of the variability of total N in the experimental lakes. He commented that

The nitrogen content of a lake increases when the phosphorus input is increased, even when little or no nitrogen is added with fertiliser.

Indicators of lake trophic status

The concentration and availability of plant nutrients in a water body is determined by its catchment, which in turn is influenced by the geology. Thus waters vary in their nutrient status.

The trophic status of lakes has been defined in terms of primary production – i.e., the amount of organic carbon made by photosynthesis under each square meter of the lake's surface during a year. The measurement of primary production requires specialized skills and equipment. Rodhe (1969) gave the following values ($\text{g C m}^{-2} \text{ year}^{-1}$):

- Oligotrophic 7–25
- Eutrophic (natural) 75–250
- Eutrophic (polluted) 350–700

Trophic status has also been defined, using more easily measured variables to categorize the trophic status of freshwater, by the Organisation for Economic

Co-operation and Development (OECD, 1982). The scheme uses information about:

- The concentration of Phosphorous (P), the limiting nutrient
- The concentration of Chlorophyll a (the green plant pigment needed in photosynthesis)
- Transparency

Transparency is measured with a *Secchi disk*. The disk is a 20 cm disk with alternating black and white quadrants. It is lowered into the water of a lake or reservoir until it can be no longer seen by the observer. This depth of disappearance, called the Secchi depth, is a measure of the *transparency* of the water. Transparency can be affected by the color of the water, algae, and suspended sediments.

The scheme has three main trophic classes:

- Oligotrophic for nutrient poor waters
- Mesotrophic for waters slightly to moderately enriched with nutrients
- Eutrophic for waters excessively enriched with nutrients

There are also two boundary classes:

- Ultra-oligotrophic for extreme nutrient deficiency
- Hypertrophic for extreme eutrophication

The trophic categories and their measurement criteria are listed in [Table 1](#).

Effects of eutrophication

Nutrient enrichment tends to stimulate phytoplankton, and one important result is increased growth of *algae* (microscopic floating plants), and *macrophytes* (larger plants). Microalgae and cyanobacteria usually grow faster than larger algae or plants. The resulting biomass absorbs light, shading out benthic microalgae or macrophytes. In flowing waters, however, phytoplankters tend to be washed downstream, and attached plants may be stimulated instead. In some freshwaters the result of enrichment is the stimulation of floating macrophytes such as duckweed (*Lemna*) or the water fern *Azolla*.

Some macrophytes form dense mats of larger floating plants such as water hyacinth, *Eichhornia* ([Figure 6](#)) and Nile cabbage. Growth results from the process of photosynthesis, which is how the plants generate organic compounds and biomass through the uptake of nutrients (nitrogen, phosphorus, and others) from the soil and water.

In the process, light acts as the energy source and carbon dioxide dissolved in water as the carbon source. As a result of the photosynthetic process oxygen is also produced.

When plants die, they decompose due to bacterial and fungal activity. In the process, oxygen is consumed, and the nutrients are released together with carbon dioxide and energy. In many lakes and reservoirs in the world, plants growing in the surface during spring and summer will die during autumn and sink to the bottom where they decompose.

During spring and summer, lakes and reservoirs are often supersaturated with oxygen due to the amount of plants. The oxygen surplus is released to the atmosphere and no longer available to decompose organic matter. This causes oxygen depletion or anoxia in the deeper layers of lakes, particularly in autumn. Oxygen depletion is therefore caused by the shifts in time and space between photosynthesis and decomposition. In tropical areas, the same process takes place, but seasonally speaking, it is not as representative as in temperate areas because temperature and daylight duration is very similar throughout the year.

Oxygen depletion often leads to complete deoxygenation or *anoxia* in the deep layers of the lake or reservoirs also because oxygen poorly dissolves in water. In shallow lakes and where plant production is high, deoxygenation of the sediment and water also occurs. Such conditions kill fish and invertebrates. In addition, ammonia and hydrogen sulfide formed by bacterial activity can be released from sediments under conditions of anoxia, and their concentrations can rise to levels which adversely affect plants and animals. Phosphorus and ammonia may also be released into the water, further enriching it with nutrients.

Some particular types of algae, which grow in highly nutrient enriched lakes and reservoirs – blue-green algae or cyanobacteria, and dinoflagellates which produce red tide – release in the water very powerful toxins which are poisonous at very low concentrations. Some of the toxins produce negative effects on the liver of livestock at minimal concentrations, but they can lead to the death of cattle and other animals even to humans when ingested in drinking water at higher concentrations.

High concentrations of nitrogen in the form of nitrate in water can also cause public health problems. They can inhibit the ability of infants to incorporate oxygen into

Eutrophication in Fresh Waters: An International Review, Table 1 OECD criteria for trophic status of lakes

Trophic category	Mean total P, $\mu\text{g L}^{-1}$	Mean $\mu\text{g Chl a L}^{-1}$	Max. $\mu\text{g Chl a L}^{-1}$	Mean Secchi depth, m	Min. Secchi depth, m
Ultra-oligotrophic	<4	<1.0	<2.5	>12	>6
Oligotrophic	<10	<2.5	<8	>6	>3
Mesotrophic	10–35	2.5–8	8–25	6–3	3–1.5
Eutrophic	>35	>8	>25	<3	<1.5
Hypertrophic	>100	>25	>75	<1.5	<0.7

their blood and so result in a condition called the blue baby syndrome or methemoglobinemia. For this to occur, nitrate levels must be above 10 mg per liter in drinking water. The condition can be life-threatening.

One of the main problems occurring as a result of algal blooms or other aquatic plants is the reduction in transparency in the water which reduces the recreational value of lakes, particularly for swimming and boating. Water hyacinth (Figure 6) and Nile cabbage can cover large areas near the shore and can float into open water spreading at times over the entire surface. These mats can block light to submerged plants and produce large quantities of dead organic matter that can lead to low oxygen concentrations and the emission of unpleasant gases such as methane and hydrogen sulfide due to its decomposition or decay. Masses of these plants can restrict access for fishing or recreational uses of lakes and reservoirs and can block irrigation and navigation channels.

Shifts in the abundance, and significant reduction in diversity of species (biodiversity), of aquatic organisms within a lake or reservoir may also be caused by eutrophication. This results from the changes in the water and food quality together with decreased oxygen concentration which often alter the composition of the fish fauna from more to less desirable species. Nevertheless, yields of certain species of fish tend to increase as eutrophication increases since there is more food available. However, oxygen depletion and high ammonia concentrations under hypertrophic conditions can lead to decreases in fish yields as eutrophication rises.

Nutrient enrichment

The growth of plants in aquatic systems is influenced by a number of factors including:

- The supply of nutrients
- Light
- Temperature
- Water flow
- Turbidity
- Zooplankton grazing
- Toxic substances

The properties of the catchment and the water body and the impact of human activities affect these factors. While it is important to understand the role of all these factors it is widely accepted that the principal factor ultimately controlling the growth of algae and plants in natural waters is the supply of *nutrients*.

In temperate freshwater systems, phosphorus is generally the key limiting nutrient. It may occur as soluble inorganic compounds such as phosphate (PO_4^{2-}) or hydrogen phosphate (HPO_4^-). It may also occur as soluble organic compounds such as proteins and lipids. Both the inorganic and organic compounds may also strongly absorb to or react with mineral surfaces, including clays and colloidal materials, and therefore be transported with fine particulates in the water. Chemical and microbial processes in the soil,

water, and sediments can transform the phosphorus from one compound to another, and affect its availability as a nutrient. Hence concentrations of phosphorus are normally reported as the element P rather than say the concentration of the phosphate ion (PO_4^{2-}). However, phosphate, either dissolved or bound to particulate matter, is normally the phosphorus compound directly responsible for the majority of eutrophication events in freshwaters.

There are exceptions. In some freshwaters silicon may limit blooms of diatoms in spring. In areas where phosphate levels are naturally high because of the underlying geology, water bodies may be limited by nitrate (NO_3^-), as in the meres of Shropshire and Cheshire in the UK. Estuaries may be limited by phosphorous at their freshwater extreme, grading through to nitrogen-limitation at their seaward end. But the common occurrence of suspended sediments and consequential turbidity in estuaries often means that light limits algal growth. Where nutrients are the limiting factor in coastal waters nitrogen as nitrate is generally believed to be the key nutrient. This is supported by recent Australian research.

Australian science has made rapid advances in the last decade in understanding eutrophication processes in inland waters and estuaries. The freshwater research on which these advances are based was triggered by well-publicized blooms of cyanobacteria during the 1980s and early 1990s, particularly a 1,000-km long bloom on the Darling River. In estuaries the study which greatly enhanced understanding and served to stimulate further research into estuarine eutrophication, the Port Phillip Bay Study, was initially designed to address perceived problems of toxicants in the Bay but provided profound insights into drivers for, and ecosystem responses to, eutrophication. Subsequent estuarine research has largely been stimulated by management questions arising from Australia's increasing coastal development for residential purposes. The research has shown that some of the beliefs extant at the time of the blooms were incorrect. For example, it is now clear that stratification and light penetration, not nutrient availability, are the triggers for blooms in the impounded rivers of south eastern Australia, although nutrient exhaustion limits the biomass of blooms. Again, nitrogen seems to play as important a role as phosphorus does in controlling the biomass of these freshwater blooms. The research has also shown that aspects of eutrophication, such as nutrient transport, are dominated by different processes in different parts of Australia. Many of the biophysical processes involved in eutrophication have now been quantified sufficiently for models to be developed of such processes as sediment–nutrient release, stratification, turbidity, and algal growth in both freshwater and estuarine systems. In some cases the models are reliable enough for the knowledge gained in particular water bodies to be applied elsewhere. Thus, there is now a firm scientific foundation for managers to rely upon when managing algal blooms.

Sources of nutrients

Although some waters are naturally eutrophic, enrichment from nutrient sources, and accelerated consequential impacts, can occur because of human activities.

Nutrient sources are either *point* sources or *diffuse* sources.

Point sources include:

- Effluent from sewage treatment works
- Industrial effluents
- Fish farms

Diffuse sources include:

- Fertilizer, livestock manure and sludge applied to land
- Overflows from septic tanks and leakage from sewers

Most attention has been paid to tackling point sources, such as sewage treatment works, since this has proved easier than tackling diffuse sources. However, as directives are put in place to tackling sewage treatment inputs to areas of conservation importance, diffuse sources are receiving more attention.

What constitutes a point or diffuse nutrient source is not always obvious. For example, atmospheric deposition and agriculture are classed as diffuse sources, as is urban runoff, but sewage treatment works are classed as point sources, even though a proportion of the nutrient load to them is diffuse in origin. Human waste to rivers via sewage treatment works is regarded as a point source, but this is derived from a population that occupies the same area from which “diffuse” urban runoff is derived. In agriculture, a significant proportion of the pollutant load is generated from small point sources, such as a farmyard. In an agricultural context, the categorization of nutrient loads into point and diffuse sources is largely a scale issue, with small point sources regarded as diffuse pollution on a catchment scale, but increasingly as point sources as the spatial resolution of observation increases. Nutrient enrichment of inland and tidal waters is considered by the European Environment Agency to be one of the most important issues to facing Europe. However, this enrichment is heterogeneously distributed both throughout Europe and within the UK. On a national and European basis, diffuse source-derived P is typically estimated to constitute some 40–60% of the surface water nutrient budget, while diffuse source-derived N accounts for approximately 70–80% of the nitrogen load. In groundwater, a higher proportion (often >95%) of the nitrogen budget is derived from diffuse sources.

Effects of nutrient enrichment

The consequences of enhanced growth of freshwater phytoplankton stimulated by nutrient enrichment include:

- Effects on water quality caused by algal blooms; these include disturbing changes to a lake’s appearance and smell as a bloom grows or decays, and the release of colored organic compounds and toxins into the water – the latter is a particular problem if the lake is a drinking

water reservoir, because the toxins are not always removed by standard potable water treatments.

- Increased hypolimnetic deoxygenation (as enhanced organic production sinks into deeper water) and consequential effects on benthic animals and fish living near the lake bed.
- More general effects on lake food webs, such as those resulting from increased dominance of chain-forming cyanobacteria which zooplankters find noxious or difficult to ingest.

Sometimes there has been explicit or unintentional confusion of the effects of plant nutrient enrichment and the effects of BOD addition (and the oxygen-consuming decay of organic material releasing nutrients which secondarily stimulate more organic production). The first can lead to the production of extra organic matter which consumes oxygen when it decays. The second involves the oxygen-consuming decay of organic material, which can release mineral nutrients which secondarily stimulate more organic production.

As argued by Lund (1972), it is best to restrict the term “eutrophic” to effects stimulated by plant nutrients. The distinction between *allochthonous* (external) and *autochthonous* (local) production is useful. BOD is the result of allochthonous production; nutrient enrichment stimulates autochthonous production.

Overgrowth and oxygen deficiency

Urban and industrial emissions of wastewater were one of the first environmental problems to become universally apparent. They were already causing problems in the UK at the beginning of the twentieth century, in the form of “stenches, filth, and infection.” Their abundant content of *organic material* was gradually broken down by microorganisms in the water, but degradation of this kind consumes oxygen, producing knock-on effects in the form of oxygen deficiency and fish kill.

Vegetation densified along banks and shores, plankton algae became increasingly abundant, and dead plants and animals accumulated in ever-thicker benthic layers. In this way, the polluted lakes and coastal inlets gradually silted up, and the open expanses of water grew smaller. Lake overgrowth is partly a natural process which has been going on ever since the lakes were formed after the glacial period. But the anthropogenic eutrophication of recent years has drastically accelerated the process in many places.

Elimination of species

The effects of a moderate eutrophication of originally nutrient-poor water are not entirely negative. Increased growth of algae and other vegetation can be beneficial to the aquatic fauna, at least to begin with. Fish production rises, for example. If, on the other hand, eutrophication continues, plankton growth becomes so heavy as to cloud the water. The resultant darkness below the surface is harmful to the benthic vegetation. The process favors

plankton-eating “coarse fish” like the roach and bream, while depleting the numbers of the predator fish species more sought after for human consumption.

In highly nutrient-rich waters, plankton production can be copious. Certain plankton species appear intermittently in massive quantities. These are called *algal blooms*. Such algae can give the water an unpleasant smell or taste, and some are even poisonous. Intensive algal production has the same consequences as if the water had received organic material from a pollution source: a large part of the oxygen content of the water is consumed when these masses of plankton die, sink to the bottom and are degraded. Oxygen deficiency can eliminate benthic life and sometimes fish as well. If the benthic water becomes completely de-oxygenated, hydrogen sulfide – toxic to all higher forms of life – is formed instead.

Heavy eutrophication entails a distinct reduction in the number of plant and animal species in the water. A few species benefit, but at the expense of all the others.

Drinking water supply

Excessive algal growth in raw water reservoirs can cause severe problems with water treatment and supply. With the predicted global warming trend, problems of this nature could become more frequent and acute. The implementation of effective measures to control the problem will take on increasing importance. Several immediate measures exist to control the excessive growth of algae or other aquatic plants. Practical control measures include:

- The corraling and removal of algal scums
- Destratification
- Weed-cutting and removal
- Barley straw application
- Biomanipulation techniques which alter the fish community

These measures are described in more detail in the section on *Reservoir Management*. The effects of these measures are often temporary and reversible.

In the longer-term, the direct control of external nutrient sources includes:

- Removal of nutrients from sewage effluents
- Targeted farm advisory visits in which nutrient and waste management plans are drawn up
- Treatment of fish farm effluents
- Treatment of urban and highway run-off

Control of internal nutrient loadings can also form an important step in the restoration of waters affected by eutrophication. Potential control measures include:

- Flushing with low nutrient water
- Removing nutrient-rich sediments by suction dredging
- Aerating the lower layers of a stratified water
- Removing nutrients by harvesting of biomass

Water treatment problems

Growth of algae in raw water reservoirs can cause problems for water treatment and supply, in relation to:

- Rapid blockage of filters, causing short filter runs and reduced throughput and/or increased volumes of wastewater from backwashing
- Increased dissolved organic carbon (DOC) in treated water from algal polysaccharide, which can result in customer complaints and increased chlorination by-product concentrations
- Penetration of algae through filters
- Taste and odor problems
- Production of toxins

Examples of common water treatment problems associated with algal types are given in [Table 2](#).

The most common cyanotoxins produced by blue-green algae in European waters are microcystins and anatoxins. The World Health Organization has set a drinking water provisional Guideline Value of 1.0 µg/L for microcystin-LR, one of the most commonly occurring cyanotoxins. These toxins can occur within algal cells (intracellular or cell-bound toxin) or be released from cells to the surrounding water (extracellular toxin). An algal bloom with 100,000 *Microcystis* cells per mL could contain 20 µg/L microcystin.

The production of the taste and odor compounds geosmin and methyl isoborneol (MIB) is known to occur by many blue-green algal species in rivers and, more significantly, reservoirs used for water supply e.g., *Oscillatoria*, *Microcystis*, *Anabaena* and *Aphanizomenon*. The musty taste and odor from these compounds in drinking water is detectable at very low concentrations of less than 10 ng/L. Like cyanotoxins, geosmin and MIB can occur in both intracellular and extracellular forms. Algal cells can contain, for example, concentrations of 10⁻⁵ ng/cell, so a relatively small algal bloom of 10,000 cells/mL would produce levels of 100 ng/L.

Eutrophication in Fresh Waters: An International Review, Table 2 Examples of water treatment problems associated with algae

Algal class	Example genera	Water treatment problems
Cyanophyceae (Blue-green algae or cyanobacteria)	<i>Anabaena</i> , <i>Aphanizomenon</i> , <i>Microcystis</i> , <i>Oscillatoria</i> .	Filter blockage, taste and odor, toxic metabolites (cyanotoxins).
Chlorophyceae (Green algae)	<i>Chlorella</i> , <i>Scenedesmus</i> , <i>Spirogyra</i> .	Taste and odor, filter blockage.
Bacillariophyceae (Diatoms)	<i>Asterionella</i> , <i>Fragilaria</i> , <i>Melosira</i>	Taste and odor, filter blockage.

Prevention of algal problems in drinking water may require catchment management to prevent ingress of nutrients to water sources, reservoir management to remove nutrients or inhibit algal growth, or the installation of suitable treatment regimes to remove algal cells and their metabolites.

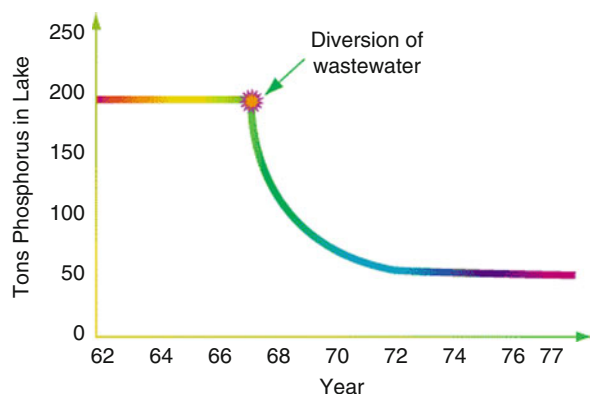
Catchment management

One of the key causative factors for algal blooms in reservoirs and rivers is nutrient concentration, particularly phosphate. Catchment management measures therefore aim to prevent excessive nutrient input. Monitoring for changes in nutrient input from point or diffuse sources, arising primarily from sewage discharges (including septic tanks and cesspits) and agriculture should be in place to identify an increased risk of blooms. Many of the factors of importance in catchment protection are outside the direct responsibility of the Water Industry and catchment management therefore relies on effective liaison with other organizations to promote good practices. Many reservoirs and feeder streams may already contain nutrient concentrations well above the threshold for algal

growth and further control of nutrient input will therefore have minimal benefit. In these circumstances, the emphasis would need to be on reservoir management to control algal blooms rather than catchment management.

International practice has shown that the best examples of success in treating eutrophication are from diversion of wastewater. Lake Washington is a good example of catchment management. Figure 3 shows declining phosphorus concentrations in this lake after diversion, which was completed in 1967.

Lough Neagh (Figure 4) is the UK's largest lake and a multipurpose resource. The Lough is a major source of drinking water and one of the most eutrophic lakes in the world due to high phosphorus (P) inputs. The P inputs to Lough Neagh have been measured and ascribed to point sources. Phosphorus from sewage works was shown to account for almost half the amount entering the lake. To curtail this source, P reduction treatment was introduced in 1981 at the ten major sewage disposal works in the Lough Neagh catchment. This was the first time P reduction treatment had been employed in the UK and it led to a reduction in P loading and improved water quality in the lake. Lough Neagh and its tributaries have been sampled at least fortnightly since 1969 and the unbroken record of nutrient inputs and water quality in the lake shows that in the early 1990s, the effects of sewage P reduction were overtaken by increasing diffuse P loads.



Eutrophication in Fresh Waters: An International Review,
Figure 3 Reduction of phosphorus in Lake Washington following wastewater diversion.



Eutrophication in Fresh Waters: An International Review,
Figure 4 Lough Neagh, Northern Ireland, UK.

Reservoir management

Reservoir management strategies can be either reactive or proactive in relation to algal growth. Reactive management in response to increased algal levels is limited to changing draw-off levels or moving the point of abstraction (if possible). Proactive control is aimed at preventing or minimizing algal blooms, including:

- *Destratification/aeration*; stratification of deeper reservoirs enhances algal growth in the warmer upper regions (epilimnion), and can cause other water quality problems as a result of low dissolved oxygen concentration in the colder deeper water (hypolimnion). A range of mixing or aeration techniques, often proprietary, has been developed to prevent stratification or provide aeration of the hypolimnion.
- *Use of barley straw*, which decomposes to release compounds that inhibit algal growth. This is currently exempted from the EU Biocidal Products Regulations but only until 2008; unless the mechanism can be clarified it may be banned.
- *Nutrient removal by plants* (e.g., reed beds, willow), situated around or at the inlet to the reservoir.
- *Chemical stripping of phosphate*; historically this has used salts of iron or aluminum, already used as coagulants in water treatment, but new technologies are available, such as "Phoslock," a proprietary material developed in Australia and applied in a pelletized form to incorporate phosphate and make it unavailable for algal growth.

- *Chemical dosing of algicides*; copper salts are used in some countries but this is not always permissible, because of its environmental impact.
- *Biological control*, using microorganisms which are pathogenic to algae or by manipulation of the animal populations within the algal food chain.
- *Ultrasound* for disruption of algal cells.

Some of these can also be reactive in relation to destroying existing blooms. The performance and acceptability of each approach will depend upon characteristics of the reservoir (e.g., size, depth), the nature of the water (e.g., hardness) and the other uses of the reservoir. Some of the techniques are well established but others, such as ultrasound and biological control, have yet to be widely demonstrated at the scale of water supply reservoirs. For many of these control techniques there will be regulatory implications and approval of, or liaison with, the appropriate environmental organizations would be needed.

Water treatment

Conventional water treatment using chemical coagulation can remove algal cells (and intracellular or cell associated products) but is largely ineffective for removing extracellular toxins or taste and odor compounds. These require more extensive treatment using, for example, activated carbon or oxidants such as ozone. Some treatments, particularly using oxidants, can break down algal cells and release toxin or taste and odor compounds, and care is therefore needed in operating these processes to avoid creating additional treatment problems downstream. Concerns over by-product formation need also to be taken into account in any treatment strategy using oxidants.

A number of approaches can be used to reduce treatment problems directly associated with the load of algal solids. These include:

- Pretreatment using microstrainers or flotation to reduce algal loads to the main treatment units
- Modification to the coagulation conditions to improve removal or reduce coagulant/algal solids loading
- Use of an oxidant prior to coagulation to enhance its performance
- Use of alternative filter media, such as dual media or multi-media, principally to increase filter run lengths
- Use of prefilters or polishing filters

Ozonation is highly effective for cyanotoxin degradation. Oxidation using potassium permanganate is also effective but relatively high doses may be needed for application to raw waters rather than to part-treated water within the treatment process. Chlorination under typical water treatment conditions is effective for microcystins but not for anatoxins. Low doses of oxidants to raw water can increase the concentration of extracellular cyanotoxin as a result of cell lysis.

Activated carbon adsorption is moderately effective for both microcystin and anatoxin, and removal by granular activated carbon (GAC) can be enhanced by biological

activity in the bed. Performance is dependent upon the type of carbon. For powdered activated carbon (PAC), wood-based types are the most effective but even for these relatively high doses (>20 mg/L) may be needed.

Biological activity in slow sand filters may give some removal of extracellular cyanotoxin, although there is little firm evidence for this. Use of a GAC layer within the sand, applied at some works for pesticide removal, could be used to give more reliable removal.

Of the oxidants used in water treatment, only ozone is effective for geosmin and MIB removal, although relatively high doses can be needed. Geosmin is more readily oxidized than MIB and is also more amenable to removal by activated carbon. GAC can be effective for taste and odor removal, even at relatively short empty bed contact times. However, longer contact times of 15 min or more can enhance removal by increased biological activity. Doses of PAC needed for geosmin and MIB are similar to those required for cyanotoxin removal.

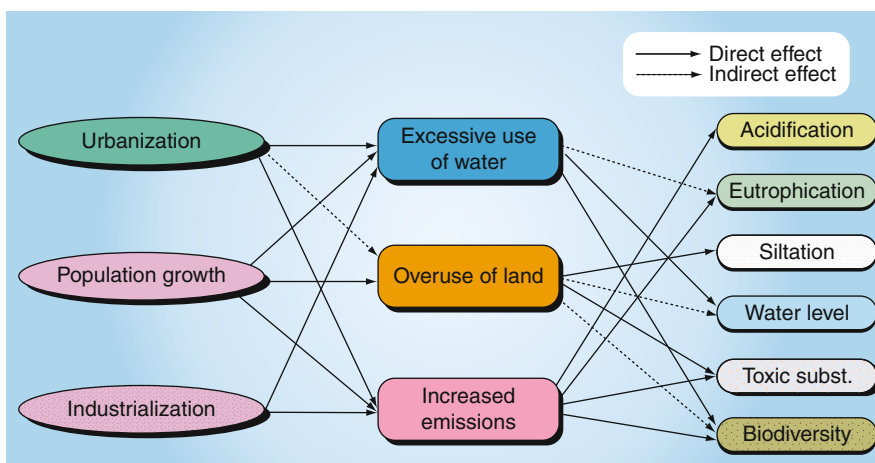
Monitoring

It is important to have an effective algal monitoring strategy in place for control of reservoir and treatment management regimes. Monitoring and management of large reservoirs can be highly demanding in relation to cost and staff time, and monitoring technology may have an increasing role in future to help make best use of often limited resources. Instruments are available based on fluorescence measurement of pigments, which may indicate the predominant algal types and the nature of the risk to treatment, from the fluorescence profile. A hierarchy of monitoring procedures can be identified, ranging from routine visual inspections of the reservoir through to laboratory analysis for toxins, with the objective of identifying increased risk of cyanotoxin bloom formation and managing the risk through increased levels of monitoring and appropriate operational actions.

Case study examples of eutrophication and water quality management

The International Lake Environment Committee (ILEC), in cooperation with the United Nations Environment Programme (UNEP), undertook a project entitled "Survey of the State of the World Lakes." This aimed to collect and compile environmental data on many important lakes of the world. Sets of detailed data from 217 lakes worldwide were gathered as a result of this project – it was possible to identify six major environmental problems, all having a significant impact on water quality, eutrophication being one of them. In addition, all six environmental problems are interrelated and to a certain extent compound the problems. All are caused by the same three basic factors (Figure 5).

All 217 lakes included in the ILEC survey showed an increase in the level of eutrophication over the past 50 years. For a number of lakes in industrialized countries, wastewater treatment to remove nitrogen and/or phosphorus has stopped water-quality degradation. By 2000 nutrient inputs



Eutrophication in Fresh Waters: An International Review, Figure 5 The basic factors which cause environmental problems in lakes and reservoirs.

to 66 world lakes were reduced. Even so, most are still more eutrophied (nutrients concentration is higher) today than they were 50–60 years ago. This is so for Lake Biwa in Japan, Lake Constance on the border between Germany, Switzerland and Austria, Lake Balaton in Hungary, Lake Mälleran in Sweden, the Great Lakes in North America and a number of North European lakes. Some case study examples are described in the following sections.

Lake Victoria, Uganda

The water hyacinth, *Eichhornia crassipes*, is a flowering plant with a native range in the Amazon areas of South America. It is one of the main exotic aquatic weeds (the other is *Salvinia molesta*) to have invaded East African freshwater ecosystems in the last decades. Although the presence of water hyacinth in Lake Victoria was reported in 1989, it is suspected that the weed may have gained entry to the lake via the Kagera River (from Rwanda) as early as 1981 (Taylor, 1993). Therefore the spread of water hyacinth in East Africa, particularly in Uganda, may have been from several sources.

In Lake Victoria (Figure 6), water hyacinth is especially concentrated in Ugandan waters, partly because the prevailing southerly winds blow mats from the mouth of the Kagera River. Increased nutrient loads into the lake also seem to have spurred water hyacinth infestations, particularly in bays receiving municipal sewage. There are several modes of hyacinth mats occurring in Lake Victoria. These include: Mobile mats; resident shoreline fringe mats; rooted colonies; successional forms found in association with other wetland plants; and mat concentrations in nutrient-rich habitats. The location, size, and form of water hyacinth mats are therefore highly variable, with some mats reaching 300 ha in cover, others infesting entire bays or drifting about the lake. The main negative effects of the increasing infestations of water hyacinth mats are:



Eutrophication in Fresh Waters: An International Review, Figure 6 Water Hyacinth in Lake Victoria, Uganda.

- An apparent reduction in fish population caused by smothering of breeding grounds, extensive deoxygenation in some areas, and increased debris loads over feeding grounds

- An increased habitat for disease vectors (*Biomphalaria* bilharzia snails), mosquitoes, snakes, etc.
- An alteration of the natural wetland fringe through successional patterns, and elimination of underwater plants and enhydrophytes in general

There are also a variety of socio-economically detrimental effects of water hyacinth. These include:

- Physical threats to water-based utilities, especially the national hydroelectric power station in Uganda, and to water intakes, in addition to increased operational costs for purifying and pumping the water
- Physical interference to water supply for rural communities
- Physical interference with fishing operations (entanglements or loss of nets), especially in fishing grounds, at fish landings, and around piers
- Blockage of commercial transport routes and communications between islands
- Increased operational costs for commercial vessels

Controlling water hyacinth on Lake Victoria and preventing its spread to other water bodies involves intergovernmental agencies and requires regional cooperation. Various control options exist (physical/manual, mechanical, chemical, biological, utilization, and environmental manipulation), but identifying the most efficient, viable and environmentally friendly option combination for Lake Victoria remains elusive. Manual and mechanical control measures have had little impact. Biological control may be regarded as a viable but expensive option and takes many years to show impact.

Although the use of chemicals to control the weed has been used in some countries, there are reservations about its perceived environmental, socioeconomic and political implications. In considering the option, fears have been expressed regarding the contamination of water for domestic and livestock use of the rural communities living close to the lake.

A solution to eutrophication in the developing countries is urgent since stopping eutrophication becomes more and more difficult and expensive every year it is postponed due to increasing nutrient accumulation in sediments.

Lake Biwa, Japan

The eutrophication of Lake Biwa began in the 1960s when the postwar economic growth of Japan began. The plant biomass concentration in the 1980s was about 10 times than that in the 1950s. Thirteen million people depend on the water supply from the Lake Biwa/Yodo River system. Since 1969, unpleasant odors in tap water from Lake Biwa have annoyed users every summer.

Plankton biomass peaked in the late 1970s, when blooms of red algae also appeared as a "freshwater red tide." This has occurred almost annually since then. Blooms of blue-green algae have appeared since 1983, a sign of more advanced eutrophication.

Trends in the degradation of water quality in Lake Biwa have now more or less leveled off, following cooperative

efforts of the residents and local government of Shiga Prefecture. Advanced wastewater treatment was introduced. The use of detergents based on polyphosphates was banned. And wetlands were constructed to cope with drainage water from agriculture. As a result of these measures, the degradation of water quality stopped, but no signs of further improvements have yet appeared. A more extensive abatement of diffuse pollution is probably needed before water quality improves significantly.

Lake Fure, Denmark

Lake Fure is a typical example of water management in Northern Europe. As in many other European lakes, the eutrophication of Lake Fure began in the 1960s. Lake Fure is situated only 15–20 km from Copenhagen in an attractive area with several lakes and forests. The population close to Lake Fure was therefore growing in the decades after the Second World War, with increased impact on the nature in the area, including lakes. At the start of the century, the transparency of the lake water was several meters, while in the late 1960s it was only 1.2 m during the spring and summer blooms.

In the early 1970s it was decided to expand treatment of the wastewater from about 30,000 inhabitants to include nutrient removal (98% removal of phosphorus). Wastewater from another 100,000 inhabitants was diverted to the sea. By these measures the phosphorus loading was reduced from 33 to 2.5 t per year. The remaining phosphorus loading comes from storm water overflow, from the treated wastewater and from diffuse sources.

As a result of these efforts, the transparency has almost doubled since the late 1960s. However, the lake has a water retention time of 20 years, which explains why even larger improvements have not yet been observed. Only a little more than 20 years have passed since measures were commenced, and 2–4 retention times are usually needed to see the full effect of the measures taken. While, the external phosphorous loading (mainly wastewater) has been reduced to 2.5 t/year, the internal loading, i.e., the loading from the sediment is still about 12 t/year. Consequently, other methods have been considered to restore the lake. However, on a long-term basis, it is still beneficial to reduce external loads of phosphorus to less than 1 t/year. This can be done by proper treatment of storm water overflow, and by increasing phosphorus removal efficiency by the wastewater treatment to 99% or more. In Lake Fure, diffuse pollution is less important, as the lake is more or less surrounded by wetlands and forest.

Extensive wastewater treatment involving nutrient removal has been introduced for many lakes in northern Europe, but, as Lake Fure shows, a long time will elapse before the full effect of this treatment can be observed. In addition, further reduction of nutrients is needed before an adequate reduction in eutrophication can be expected. In most cases nonpoint (diffuse) source pollution will be needed to be reduced considerably – clearly a much more difficult task than reducing point source pollution.

North American Great Lakes

Approximately 30% of Canada's population and 20% of the US population live in the Great Lakes drainage basin, some 520,000 km². The Great Lakes comprise: Lake Superior, Lake Michigan, Lake Ontario, Lake Erie and Lake Huron. 24 million people depend on these lakes for drinking water. Industrial growth in the 1940s and 1950s resulted in oil pollution and eutrophication accelerated in the 1960s. By the late 1960s, water quality had deteriorated to a critical level. Massive algal blooms were frequent, and severe oxygen depletion occurred, even in the central bottom water of Lake Erie. Massive fish die-offs took place in Lake Michigan and Lake Ontario.

In response to this situation, specific effluent standards were established in the early 1970s. Phosphorus removal was introduced in wastewater treatment plants, and phosphorus content in laundry detergent was reduced from 30–40% to 5%.

By the early 1980s, the phosphorus loading approached the target established 10 years earlier. In Lake Erie and Lake Ontario, it was reduced by 20%, but overall the reductions in the Upper Great Lakes were only about 50%. These reductions were also reflected in the total phosphorus concentrations and phytoplankton concentrations in the open water of Lakes Erie and Ontario. These reductions were only to about one third of the 1970 peak values. Again, reductions of non-point sources of phosphorus and nitrogen to the same extent as for municipal wastewater were not possible. However, measures to abate eutrophication of the Great Lakes are among the most successful lake management case studies, because point source pollution was the major source of nutrients discharged to the lakes.

Preventing eutrophication – European directives

In addition to local eutrophication control, the European Commission has adopted legislation, which applies to all Member States in the European Union, for the control of eutrophication either directly or indirectly at a national level. The relevant Directives, which all aim to limit pollution, are described below:

- The Urban Waste Water Treatment Directive

This Directive sets minimum standards for the provision of sewage collection and treatment. Discharges of greater than 10,000 population equivalent to waters identified by Member States as sensitive to eutrophication – termed “Sensitive Areas (Eutrophic)” – must comply with specified standards for phosphorus and/or nitrogen (depending on the situation), in addition to a requirement for secondary sewage treatment.

- The Nitrate Directive

This Directive has an objective to “reduce water pollution by nitrates from agricultural sources, and to prevent further such pollution.” A water body is identified as polluted if it shows signs of eutrophication – induced

by excess nitrates – or if it is used for drinking water abstraction and has elevated concentrations of nitrate.

- The Habitats Directive

This Directive enables the designation of Special Areas of Conservation (SACs) in which rare and endangered habitats and species must be protected. If eutrophication threatens the conservation status of such areas there may be a need to impose nutrient control requirements on discharges, where appropriate. The environment regulators have a duty to review discharge consents to ensure that the designated sites are adequately protected.

- The Wild Birds Directive

This Directive gives the same protection against discharges to sites designated as Special Protection Areas (SPAs).

The Water Framework Directive incorporates the requirements of the existing Directives, supplemented by whatever additional measures are needed to control pollution sources, both point and diffuse, to achieve the stated objective. It is therefore an essential vehicle for the control of eutrophication, providing a coordinated approach to sustainable water management through river-basin management plans, assessing the state of waters and the sources of pollution, then formulating and implementing improvement plans. The objective is to achieve good ecological quality, which will include avoidance of the effects of eutrophication.

In addition to the EC Directives, there is a range of international commitments, elements of which are of direct relevance to eutrophication control:

The Earth Summit Conference in Rio de Janeiro in 1992 resulted in the UK entering into commitments to safeguard the well being of the planet. A UK Biodiversity Group has been set up to take forward the Government's commitments to preventing the loss of species and habitat, under the UK Biodiversity Action Plan. Action Plans for priority habitats and species are being developed including those to protect mesotrophic lakes and eutrophic standing waters where control of eutrophication will be important in maintaining or restoring biodiversity.

The identification and control of diffuse agricultural sources of nutrients present the greatest challenges. There are increasing pressures on the agricultural industry to develop more environmentally sustainable farming methods. In England and Wales this is being implemented through agri-environment schemes where grants are offered for farming in a more environmentally sympathetic manner.

Preventing eutrophication – public awareness and education

The few, partial success stories concerning eutrophication abatement have all involved strong public support by communities and stakeholders combined with effective legislative measures and monitoring programs. The best results were obtained when control measures began early and long before hyper-eutrophication occurred. Generally,

problems involving point sources were relatively easily solved, while those involving nonpoint diffuse sources were more difficult to resolve.

Although water authorities can construct wastewater treatment plants with adequate nutrient removal, a constant awareness about water quality can only be maintained by public engagement. The final reduction of nutrients to a lake requires effective reduction of diffuse sources and this must involve the wider community. For full success, community residents must be partners in the environmental management strategy.

Using less detergents and detergents with no or little polyphosphates can reduce phosphorus loads considerably. A campaign in Poland to reduce phosphates from laundry was aimed at the whole Polish population and was very successful. The phosphorus loading in many towns and villages fell by more than 20%. The results of the campaign were monitored to encourage stakeholders to continue efforts. The campaign also increased the general environmental awareness of the public and made them aware of the direct effects of laundry detergent on eutrophication.

Reduction of nonpoint pollution in areas with extensive agriculture requires the construction of wetlands as a buffer between fields and rivers and lakes. This is, however, not sufficient of itself, but must be supported by a massive campaign to persuade farmers to use less fertilizers. The final 10–20% of fertilizers applied has almost no effect on agricultural yield, but can contribute significantly to nutrient concentrations in drainage water. A campaign in Denmark in the early 1990s resulted in some reduction of diffuse pollution, probably because the farmers calculated that they saved money by reducing fertilizers. The reduction, however, was not sufficient – a green tax on fertilizers was considered but has not yet been introduced.

Active participation by communities in abating eutrophication is impossible without their understanding of the problem. This requires environmental education of communities. In many industrialized countries a number of leaflets and booklets on environmental information are distributed free to the public. These give information needed by citizens to enjoy their environment and to take an active part in the debate.

In 1987, UNESCO defined environmental education as follows:

Environmental education is a permanent process in which individuals gain awareness of their environment and acquire the knowledge, values, skills, experiences and also the determination which enable them to act – individually and collectively – to solve present and future environmental problems. It is therefore a continuous, lifelong process.

Glossary of terms

Anoxia, anoxic conditions No oxygen present.

Bio-manipulation Change in biological structure by removing and/or stocking living organisms.

Chlorophyll a The green pigment in plants that promotes photosynthesis.

Epilimnion See *Thermocline below*.

Eutrophic Nutrient rich.

External loading Nutrients from outside the lake, for instance nutrients in wastewater discharge to the lake, or nutrients from agricultural drainage water.

Hypolimnion See *Thermocline below*.

Internal loading Nutrients from the lake itself, for instance release of nutrients or toxic substances from the sediment (the muddy bottom layer) of the lake.

Mechanical-biological treatment Treatment of wastewater by settling of suspended matter together with the use of microorganisms to decompose organic matter. Only minor amounts of nutrients (nitrogen and phosphorus) are removed by this treatment.

Nonpoint source (diffuse) pollution Pollution mainly from agriculture or dumping grounds. It is difficult to collect for treatment.

Photosynthesis Formation of plant biomass from nutrients with solar radiation as the energy source.

Phytoplankton Free-floating microscopic plants.

Point source pollution Polluted water from a defined point. It can be collected as industrial or municipal wastewater and treated by what is often called end-of-pipe technology (environmental technology).

Sediment The bottom and often muddy layer of a lake.

Thermocline The level dividing a lake into two layers, an upper warmer one (epilimnion) and a lower colder one (hypolimnion). The temperature usually drops several degrees centigrade over just a few meters at this level.

Zooplankton Microscopic to very small free-floating animals.

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Cross-references

Brownification of Lakes
 Cyanobacteria (Blue-Green Algae)
 Finnish Lakes, Trends and Regional Differences of Phytoplankton
 Microorganisms in Lakes and Reservoirs
 Nutrient Balance, Light, and Primary Production
 Phosphor Exchange Sediment-Water
 Trophic Lake Classification

EVERGLADES, FLORIDA, USA

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Introduction

The “river of grass” label often attributed to the Everglades (Douglas, 1947) still holds true in many parts of this impressive subtropical wetland system, and is clearly visible to those who have flown over South Florida. From

the ground, the river of grass is also apparent but the distinctive landscape patterns are less easily detected. In reality, the Everglades landscape contains a multitude of wetland types including sawgrass (*Cladium* spp) marshes, sloughs, marl- and peat-based wet prairies, tree islands, pinelands, and, at its southernmost extreme, mangroves and the Florida Bay estuary. Before major human influence, the Everglades landscape was even more diverse and included custard apple swamps, short-hydroperiod wet prairies, and cypress strands (Davis et al., 1994).

Access to this wetland system is difficult. Airboat travel is the norm, and aside from the limited geographical area covered by tourist concession airboats, few venture deep into the interior wetlands. Once there, however, the visitor is welcomed by a plethora of intriguing biological utterances, magnificent but greatly diminished wading bird populations (Ogden, 1994), occasional bellowing alligators, sometimes searing heat, and, depending on the area and season, biting and sucking insects of impressive numbers and noise.

At one time, the Everglades covered about 1.2 million hectares, extending south from Lake Okeechobee to the peninsular tip of Florida, east to the coastal ridge (with occasional connections to the sea through areas known as the transverse glades), and west to the Immokalee Ridge (roughly the border of the Big Cypress National Preserve). An area of 283,290 ha immediately south of Lake Okeechobee that was once sawgrass marsh is now, however, dominated by agricultural uses (primarily sugarcane). Additional areas along the eastern border of the Everglades that were once cypress stands are now urban areas. This loss of about half of the original Everglades wetland area has resulted in a loss of habitat diversity, including that required for wading bird foraging, a reduction of total areal productivity, and a loss of three major vegetation communities.

Formation of the Everglades occurred largely in recent geological time, about 5,000 years ago. Water historically flowed slowly in a southerly direction from Lake Okeechobee to Florida Bay, creating conditions favorable for development of an underlying peat deposit that is one of the world's largest. In the late nineteenth century, construction of canals was initiated to drain the Everglades to make it suitable for agriculture. About a century later, thousands of kilometers of canals and levees had been built, providing not only land for agriculture but also accomplishing flood control and water supply objectives. What resulted from these canals and the large pumps that move water through them, collectively known as the Central and Southern Florida (C&SF) project, was lowered water tables, altered hydropatterns, and transport of vast quantities of freshwater to the ocean that would have naturally flowed down the Shark River and Taylor Sloughs into the Gulf of Mexico and Florida Bay (Light and Dineen, 1994). A system once characterized by hydrological sheet flow had become a highly compartmentalized and regulated system.

High phosphorus concentrations in Lake Okeechobee and excess nutrient runoff (eutrophication) from the Everglades Agricultural Area (EAA) have contributed to shifts of vegetation communities in the Water Conservation Areas (WCAs) from sawgrass to cattail. Nutrient runoff from the EAA has resulted from fertilizer application and through oxidation of the peat soils due to agricultural water management practices. Oxidation and other factors have led to an average annual soil subsidence rate of approximately 2.5 cm. In the EAA this has led to more than 2 m of soil loss since the first canals were dug in the 1920s (Sklar et al., 2005). Eutrophication and changed hydropatterns have altered the extent and coverage of naturally occurring fires, and have provided areas more suitable for successful invasion of exotic species such as *Melaleuca* and *Casaurina*. *Melaleuca* presents a significant problem because of its potential to spread, its ability to outcompete native vegetation, and its high evapotranspiration potential. The latter could have a significant impact on the water budget of South Florida and the ability to satisfy water demands by urban, agricultural, and natural systems.

Although there is little disagreement that the Everglades have been regrettably altered during the last century, there is considerable discussion about what a restored system should look like. Should it be based on the vegetation patterns that existed before human influence? Were these patterns constant or constantly changing? What hydropattern and nutrient levels would be conducive to restore the landscape? Because half of the Everglades has been lost to agriculture and urban uses, should the restoration goal be to reproduce the original Everglades in half the space? Alternatively, should restoration efforts return the Everglades that remains to short-hydroperiod wetlands that existed on the edges of the original Everglades? In addition, can sufficient restorative water be sent to Florida Bay through the extant Everglades without adversely affecting upstream hydropattern restoration efforts?

Determining how to accomplish an Everglades restoration while sustaining agricultural and urban systems of South Florida is the subject of intense debate and the focus of major scientific and engineering programs. The first big step was implementation of best management practices (BMP) in the EAA and in the watershed tributaries of Lake Okeechobee. The second big step was the construction of about 25,000 ha of ecologically engineered wetlands called Stormwater Treatment Areas (STAs) for reduction of EAA phosphorus runoff. The combination of BMPs and STAs, as well as future nutrient reduction

technologies, is intended to achieve reductions in phosphorus loads and concentrations that will protect the Everglades from imbalances of flora and fauna.

The Comprehensive Everglades Restoration Plan (CERP), approved jointly by the U.S. Congress and Florida in 2000, created additional restoration efforts with a focus on identifying historical hydropatterns, hydrology needs of the Everglades, and engineering solutions to achieve the needed water distribution, depth, and timing of delivery. CERP is expected to first “decompartmentalize” the Everglades, which is divided into five “compartments” by a system of canals and levees that prevent water from moving freely across the landscape. These compartments produce excessive dry downs that cause tree island and peat fires in their upstream reaches and excessive flooding that cause tree island degradation and habitat loss in their southern reaches. Downstream of these five compartments and separated from them by the old Tamiami Trail Road is the Everglades National Park. The restoration of the hydrology of this park will depend upon the designs that are selected for the raising and lifting of Tamiami Trail, the identification of new sources of water, and the management of groundwater seepage from the park into flood-prone residential areas.

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Cross-references

[Deltaic Swamps](#)
[Floodplain Wetlands: Focusing on India](#)
[Okeechobee, Lake, Florida, USA](#)
[Wetlands](#)

F

FENS, ENGLAND

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Introduction

The Fens are unique with a history and character all of their own. This area of England fans out from the Wash across Cambridgeshire, Lincolnshire, and West Norfolk, UK. Once an inhospitable swampy wilderness, the Fens have been tamed to leave us today with a network of intricate waterways, which are renowned as some of Britain's most atmospheric and tranquil.

An immediate problem in providing any brief summary of fens is that ecologists themselves differ in how they use the term. Firstly it is necessary to distinguish “fen” as an ecological term from “Fenland” as a geographical entity.

Fenland, a geographical area of East Anglia

Geographically, Fenland is the ancient area of marshes on the vast floodplain that surrounded the rivers Witham, Welland, Nene, and Ouse (and their subsidiaries) that drain much of central and eastern England and flow into the Wash between Norfolk and Lincolnshire. It is or was an area of several hundred square miles (3,800 km²) and, in postglacial times, evidently continued much further still into what is now the North Sea. It extended from Lincolnshire in the north to Norfolk in the southeast, encompassing much of the geographical (no longer political) country of Huntingdonshire and part of Cambridgeshire.

Perhaps one indication of the immensity of the area is the myth and legend surrounding Hereward the Wake, an ancient “Robin Hood-like” folk hero or outlaw who operated out of the Fens and who fortunately has not yet been

subjected to the same recent historical and cultural media travesties as Robin Hood.

Little of this ancient area now exists. Most is now arable farmland, a flat landscape of huge fields and drainage dyke, with few natural hedges and with scattered, surprisingly isolated human communities. A few fragments remain to provide most of our finest British examples of “fen” as an ecological concept. These include Chippenham Fen and Wicken Fen in Cambridgeshire, and Holme and Woodwalton Fens in Huntingdonshire, all of which are National Nature Reserves, though Wicken Fen, the most accessible of these, is owned and managed by the National Trust.

Though outside Fenland as defined here, there are a number of named fens stretching further east in Norfolk across to the Norfolk Broads, generally as parts of valley mire complexes. Many of the fenland rarities are or were to be found in both areas.

Fens as an ecological concept

Ecologists regularly use the word “fen” but establishing a precise definition is more difficult, reflecting the diversity and continuity of habitat and vegetation types. Generally, however, use of the term equates to the majority of *topogenous mires*, where local relief results in permanently high water tables, as on flood plains and in shallow depressions, or in transitional zones of vegetation bordering open waters. Smaller areas of fen may also occur within *soligenous mires* associated with routes of moving drainage water. It is understood here that any type of mire is generally characterized by peat formation, i.e., the buildup of incompletely decomposed organic matter under conditions of waterlogging and negligible diffusion of oxygen, though in fact some soligenous fens accumulate little or no peat, though are otherwise similar in hydrochemistry and vegetation.

The East Anglian fens are characterized by alkaline conditions resulting from water draining from chalk and other calcareous rock formations. They (and similar examples elsewhere) may be distinguished as “rich fen,” though there is often a general understanding that a “fen” will be relatively eutrophic (nutrient rich). A classic plant of rich fen is saw-sedge (or simply “sedge”) (*Cladium mariscus*), which may be a key species in past or present management (see below). The definition of “fen” however often also covers sites with much lower mineral input and corresponding higher acidity; such areas may be described as “poor fen” and are commonly characterized by extensive development of *Sphagnum* moss carpets.

Fen may be defined by a pH generally above 6.0 and with relatively high levels of calcium and bicarbonate ions. The vegetation of such mires tends to be rich in herbs and “brown mosses” such as *Drepanocladus*, *Campylium* and *Scorpidium*, and *Cratoneuron*.

By contrast, *bog* is defined by a pH generally below 5.0, with low levels of calcium ions, and with chloride and sulfate ions as the main anions. Vegetation includes members of the heather family (*Calluna*, *Erica*, etc.), cotton grasses (*Eriophorum*), and other calcifuge (“calcium-avoiding”) members of the sedge family, and often an abundance of *Sphagnum* mosses.

On this definition, many examples of so-called poor fen or acid fen are better considered as “bog,” and this gives a more satisfactory treatment of phases and microtopography in complex acid mire systems.

Plants

Herbaceous fen (including open reed and sedge fens)

The open fens are usually dominated by tall reedlike grasses, such as common reed (*Phragmites australis*), small reeds (*Calamagrostis* species) or purple moor grass (*Molinia caerulea*), or by tall sedges such as *Carex acutiformis* or *C. disticha*, or by saw-sedge (*Cladium mariscus*), or locally by the blunt-flowered rush (*Juncus subnodulosus*). A variety of other tall herbs such as meadowsweet (*Filipendula ulmaria*) may be present, perhaps along with declining rarities such as the marsh pea (*Lathyrus palustris*). Below the field layer is likely to be a layer of mosses, including *Campylium* and *Cratoneuron* species. This may be a transitional phase or may be maintained by appropriate management.

Traditional management of many of the East Anglian fens has been the cutting of “sedge” (*Cladium*), primarily for thatch. Sedge is more flexible and durable than reed and was used for ridging reed-thatched roofs or, less often, for thatching entire roofs. It also had uses as kindling material and as a tough litter for floor coverings. Large areas were maintained for this purpose, and the survival of undrained fen fragments no doubt has been due to the value of sedge as a cop. However, there is

now much less demand and former sedge fens have in many cases been colonized by bushes to form *carr*. This has meant the local disappearance of many plants requiring these open conditions and is implicated in the extensive loss of invertebrates such as the swallowtail butterfly.

While there is still a small commercial demand, cutting sedge is now largely a conservation exercise. Management aims at, e.g., Wicken Fen are not only to maintain sedge fens but also to reclaim areas from *carr* and extend the open communities.

The areas dominated by grasses such as *Calamagrostis* species or *Molinia* were traditionally cut as “litter” for animal bedding. Like the sedge fens they tend to be herb-rich, and continued cutting on an annual or biennial cycle is required to maintain floristic diversity.

As noted above, poor fens (if considered “fens” at all) are likely to have a moss layer including or dominated by *Sphagnum* species. Purple moor grass (*Molinia caerulea*), bottle sedge (*Carex rostrata*), and the smaller sedges, such as *C. echinata* and *C. nigra*, may predominate among the vascular plants.

Carr (wooded fen)

Succession to carr (wet scrub and swampy woodland) is usually to be expected except where active management maintains the open areas. Lowered water tables caused by drainage within or adjacent to the fen complex may accentuate this, and since most surviving fens are surrounded by farmland, this may be a substantial management problem.

Bushes and trees forming carr must be capable of growing in waterlogged conditions with little oxygen supply to the roots. Willows and sallows (*Salix* species) may predominate, including gray willow (*S. cinerea* subsp. *Cinerea*), which often dominates East Anglian fens and occurs more locally north to central Scotland.

Two buckthorn species, the common or purging buckthorn (*Rhamnus cathartica*) and the alder buckthorn (*Frangula alnus*) are also locally abundant carr species in some of the East Anglian fens. Common buckthorn is not confined to fen carrs; it can be a component of scrub on dry chalk slopes. Alder buckthorn is more restricted to damper habitats.

At Wicken, both were abundant in the first part of the twentieth century and *Rhamnus* still is often being the dominant carr species. *Frangula*, however, suffered a decline through apparent fungal attack in the 1930s and has suffered other misfortunes since. It is currently, however, a typical pioneer species in young carr and appears to be recovering its former status.

Alder (*Alnus glutinosa*) is a larger tree that may come to dominate richer fens in some localities. It is notable as possessing rood nodules containing a symbiotic nitrogen-fixing actinomycete. Nitrogen may otherwise be deficient during development of fen woodland.

In poor fen, the shrub bog myrtle or sweet gale (*Myrica gale*) is no doubt even more important as another species that effects nitrogen enrichment via symbiosis.

On poorer sites, downy birch (*Betula pubescens*) is likely to become the dominant tree species, sometimes forming more or less pure woodland on the thicker peats.

History

In Anglo-Saxon and medieval times, the precious areas of dry land rising above the fen attracted the attention of religious communities. In truly grand style, they founded great cathedrals and monasteries, dominating the skyline and life of the surrounding Fens.

Ely: The ancient city of Ely occupies the largest island in the Fens. In the seventh century, St. Etheldreda founded a religious community on its hill top site. Rich in folk history, Ely was the stronghold of Hereward the Wake, who used the island to stage the final Anglo-Saxon resistance against the Norman invasion.

The main development of the city originates from the late eleventh Century when construction of the cathedral commenced. Both the cathedral and the surrounding Fens have played a major role in the history of Ely through the centuries.

Today, Ely is characterized by its pattern of narrow streets and monastic buildings, gathered around the spectacular cathedral. Visitors can explore the ancient buildings and medieval gateways, stroll along the riverside, or simply enjoy the peaceful relaxed charm of this historic city. In addition to the cathedral, there is Oliver Cromwell's house or the Ely museum for a fascinating insight into the history of the city and surrounding Fens.

Elsewhere in the Fens, the abbeys at Ramsey, Thorney, and Chatteris along with Spalding Priory were influential in the development of these market towns. Ten miles south of Spalding, the small town of Crowland is dominated by the remains of its medieval abbey. Still functioning as the parish church, and featuring an interpretative exhibition, the original abbey was founded in 716 in memory to St. Guthlac. Rebuilt between 1,114 and the fifteenth century, it was on a massive scale, dominating the surrounding Fens. Another landmark in Crowland is the unique medieval triangular bridge in the center of town.

Historic wash ports

Since medieval times the historic Fen towns clustered around the Wash have developed as important ports, enjoying a busy trade with the Low Countries and the Hanseatic League of German and Baltic maritime cities. Along with Boston and King's Lynn, the towns of Wisbech and Spalding, now several miles inland, once occupied positions on the medieval coastline of the Wash. Through drainage and reclamation, the Wash coastline is very different today. However, Wisbech, now 12 miles inland, is still an active port.

Boston: Situated on the banks of the River Witham, Boston has long traditions as a port and boasts a wealth

of buildings and architecture reflecting its great trading role. The skyline is dominated by St. Botolph's Church, England's largest parish church, rising 272 ft above the River Witham. Another imposing landmark is the Maud Foster Windmill, England's tallest working windmill.

The Guildhall Museum, dating back to 1,450, depicts the town's maritime history and features a free interactive computer simulation of what life was like around 1,536. The museum also includes the cells and courtroom where the Pilgrim Fathers were tried and imprisoned. Nearby in Spain Lane, Blackfriars Arts Centre is a lively venue housed in a thirteenth century Dominican friary.

King's Lynn: Over 900 years of maritime and trading history are preserved in the historic core of King's Lynn. Still a busy port and thriving commercial center, the town's medieval churches and guildhalls, secret courtyards, and hidden alleys leading down to the river combine with the lively atmosphere of two busy marketplaces.

Market towns

Throughout the Fens you can enjoy the traditional atmosphere and friendly slow pace of historic market towns, with a lifestyle much cherished in today's fast-paced world.

The town of March, originally a small island community, developed as a Tudor Port and later as a railway town in the nineteenth century. With the Old River Nene flowing through its center, it has been described as "The Thameside town in miniature," with many attractive cottages and buildings alongside the river. The fascinating history of the town is told in the March Museum.

Similarly, the towns of Chatteris, Littleport, and Whittlesey grew from small island communities. Whittlesey is characterized by the seventeenth century Butter Cross in the center of the marketplace. The town is an interesting maze of streets with well-preserved architecture spanning several centuries.

Littleport near Ely is famous as the scene of the Littleport Riots of the nineteenth century.

Chatteris is a typical Fenland market town popular with anglers and bird watchers attracted to the surrounding Fens.

To the south of King's Lynn, the attractive town of Downham Market occupies a site on the edge of the Fens. Characterized by its unusual clock tower in the marketplace, it is an excellent base for exploring Fen villages, such as Upwell, Outwell, and Stow Bardolph.

The story of the Fens

The history of the Fens is a fascinating story of a landscape and its people, where man and nature have interacted to create the Fens environment of today. It is a story of an amazing transition from the wetland wilderness of old to the people-made landscape of today. This spans the centuries from Bronze Age, Roman, and Anglo-Saxon times, when habitation was limited to isolated islands and a wide silt ridge which formed around the Wash. Between

Domesday and the thirteenth century, a gradual reclamation of land took place by building banks as flood protection from the surrounding uplands.

The Dark Ages saw a halt to reclamation; however, by the early seventeenth century, with economic recovery, the attention of speculators turned to draining the peat fens in the south and remaining undrained silt fens further north. Under the guidance of the fourth Earl of Bedford, the speculators or adventurers started work on the systematic draining of the Fens. Experienced civil engineers were commissioned, such as the Dutch civil engineer Cornelius Vermuyden, who undertook the greatest scheme, constructing the Old and New Bedford Rivers between Earith and Denver.

Local opposition was considerable as the systematic drainage of the land threatened the traditional fishing and wildfowling rights of Fen dwellers. Their fierce resistance and destruction of the drainage work earned them the name "Fen Tigers."

Drainage schemes continued, but unexpectedly, the land began to shrink at an alarming rate as the soil dried out. As the level of the land dropped, water could no longer drain into the rivers which were by now higher than the fields. Wind pumps were introduced to pump water off the land and into the rivers, but their reliance on adequate wind and continued shrinkage of the land saw the task become increasingly difficult. It was not until steam power was introduced in the 1820s that the Fens were effectively drained.

At one time the Fens landscape was once dominated by up to 700 windmills, built in timber or brick to drain the land or mill the corn. Many have since disappeared, yet some still survive, towering over the Fens. These include Denver Mill near Downham Market, the Great Mill Haddenham, Downfield, Stevens, Wicken and Swaffham windmills south of Ely, Sibsey Trader Mill north of Boston, and Maud Foster Windmill in the town of Boston at seven stories high, the tallest working windmill in Britain.

Today there is a sophisticated network of drains, embankments, and pumps to protect the land from the ever-present threat of rain and tide.

Produce

Generations of Fen people have maintained a close kinship with the land. History, nature, and the ingenuity of man have provided a landscape unrivaled for its rich fertile soils and abundant variety of crops.

From the rich dark peaty soils in the south and west to the fertile silt of the north, wherever you go in the Fens, you will find a wide variety of different flowers, fruit, and vegetable crops being grown. Different crops are grown to suit local soils and conditions – apple orchards, soft fruit, and strawberries around Wisbech; cabbages, cauliflower, and Brussels sprouts around Boston; flower bulbs around Spalding; carrots and celery in the peat soils around Ely and Chatteris.

Throughout the seasons, the ever-changing landscape offers wonderful floral displays. Yellow carpets of daffodils in spring, vivid summer displays of roses in bloom, and spectacular flower festivals demonstrate the importance of flower growing in the Fens.

The Fens are the center of Britain's bulb and seed industry, a rich heritage proudly displayed through festivals, show gardens, and flower displays.

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Cross-references

Wetlands

Wetlands: Classification, Distribution, Function

FINNISH LAKES

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Description

From the estimated number of 10–15 million lakes in the world, well-over half are located in the northern boreal zone. In Finland, a detailed lake inventory was made in the 1980s with the following results (Kuusisto and Raatikainen, 1988):

Area (km ²)	Number of lakes
>100	47
10–100	279
1–10	2,283
0.1–1.0	13,094
0.01–0.1	40,309
0.0005–0.01	131,876

This brought the total number to 187,888, over three times higher than the previous estimate published in the 1950s. The increase was simply due to the myriad of ponds smaller than 1 ha, their number being as high as 131,876. The lower size limit was set to 0.05 ha.

In practice, these figures can naturally not be accurate to the last digit. The sizes of water bodies vary according to hydrological conditions, causing them to cross class boundaries. The shores of shallow lakes are not well defined on the basic maps 1:20,000, which were used in the work. All map sheets, 3,610 of them, were checked twice; the work took over two person-years.

Lake routes are a typical feature particularly in the Finnish Lake District. This provokes the question: when does one lake end and the next one begin? And when the river waterway settles itself, when does still water have enough plump to be a lake? These matters have a moderately good solution in the following specifications of lake definition:

- The water surface is the same at different parts of the water area, aside from temporary wind- or ice-caused exceptions.
- The outflow–volume relationship is so small that a great majority of sedimentary materials drop to the bottom.

In practical counting work, these specifications were not of great use: only in rare cases the counter was able to compare the water surface level readings marked on a map. Solutions had to be worked out by “this is how I feel” method.

Still there was a problem with the numerous small ponds on aapa mires. It was decided that they will be counted as only one water body. In such swarms, the water surface is however all the same, because all bonds are hydraulically in contact with each other.

Five river basins in Finland have slightly over 20,000 water bodies. Among those are the two largest basins, Vuoksi (52,600 km²) and Kemijoki (49,500 km²). They have lake densities of 43 and 44/100 km². The other three are located in northern Lapland with considerably higher lake densities: Paatsjoki (138/100 km²), Tenojoki (470), and Näätämöjoki (920). The topography in that region is small-scale, and in every depression there is water. One single basic map, having an area of 100 km², has as many as 1,960 water bodies, almost 90% of them being smaller than 1 ha. Alongside the Lake District, Finland thus also has the Pond District.

Not all of the lakes are fully in Finland. There are 182 shared with Russia, 120 with Norway, and 13 with Sweden. The largest lake shared with Sweden is Kilpisjärvi (37 km²), but a much larger one is shared with Russia (Kitee’s Pyhäjärvi, 200 km²).

The depth charting of Finland’s lakes began in 1856 from Tampere’s Pyhäjärvi. The work was soon continued in several large lakes in order to improve the safety of inland water transportation. The focus was first on the numerous straits and narrows.

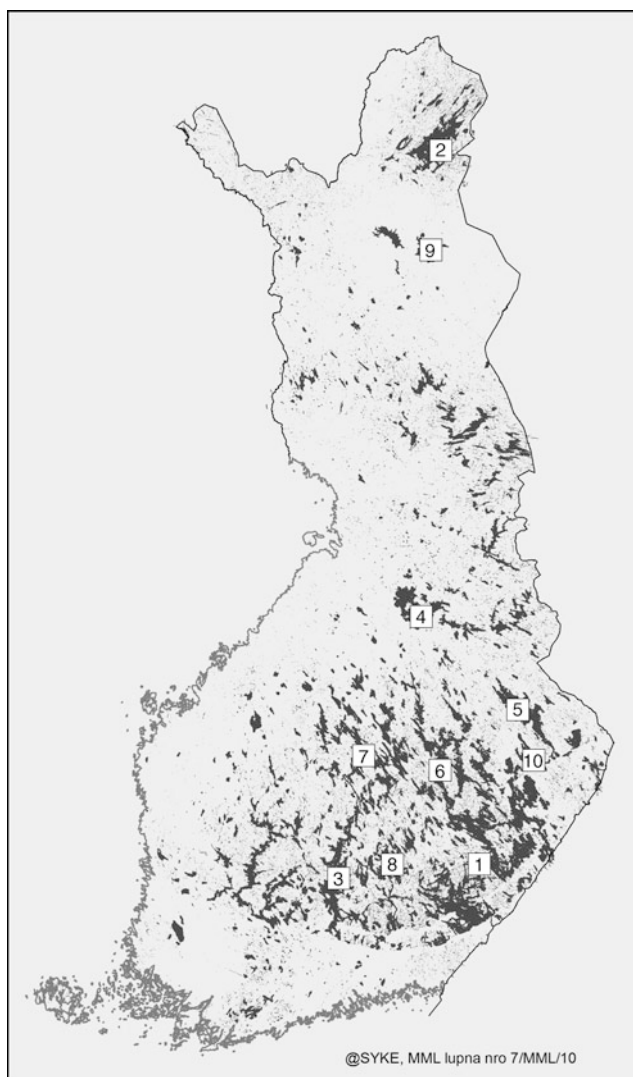
At the end of 2009, over 89% or 29,600 km² of the Finnish total lake area is mapped. Unsounded areas are decreasing by about 300 km² a year. The deepest lake is Päijänne, 95 m, followed by Inari (92 m) and Suvasvesi (90 m). Lake Suuri Jukajärvi in southeastern Finland has the highest mean depth, 23 m (Kuusisto and Hakala, 2007).

The surface of about 3,000 lakes has been lowered in Finland, most of them in the nineteenth century. The main reason was a demand for agricultural land. Quite many of those lakes dried completely, but a number of them became shallow and eutrophic. Among those are

nowadays some of the most important bird sanctuaries of the country.

Most of Finland’s large lakes were formed during the Ice Age and shaped by the land uplift. Päijänne and some other major lakes were born from faults in the bedrock formed hundreds of millions of years ago. Around ten lakes, the largest ones being Lappajärvi and Paasivesi, have been created by meteorite impacts.

Water quality is good or excellent in over 80% of Finland’s lake area, although many shallow lakes require attention. Almost 1,000 rehabilitation projects have been completed in recent decades. The most common methods are removal of aquatic plants, improvement of food chains, and oxygenation. Another factor in improving



Finnish Lakes, Figure 1 The areal distribution of lakes in Finland. There are only a few major lakes in the coastal areas. In the Lake District, water covers over one fifth of the area.

Finnish Lakes, Table 1 Ten largest lakes in Finland. Their locations are shown in [Figure 1](#)

	Name	Area (km ²)	Maximum depth (m)	Duration of ice cover (d)	Mean surface water temperature in June–August (°C)
1	Greater Saimaa	4,377	82	140	18
2	Inari	1,102	92	190	13
3	Päijänne	1,054	95	140	17
4	Oulujärvi	893	35	170	16
5	Pielinen	868	60	150	17
6	Kallavesi	513	89	150	17
7	Keitele	500	65	160	18
8	Puulavesi	325	60	140	18
9	Lokka	317	12	190	14
10	Höytiäinen	293	57	160	17

water quality has been significant investments in the removal of nutrients from urban and industrial wastewaters.

The Water Framework Directive of the EU came into effect in 2000, with the aim of achieving a high ecological status for surface waters by 2015. Collaboration is closer between authorities and local residents in Finland than in most other countries. Due to their love of local lakes and the scarcity of public funding, lakeshore residents have been inspired to start up lake protection groups and to work together in maintaining their lakes.

Many of Finland's towns are located on a lakeshore. A good example is Tampere, where the power of rapids attracted several large industrial plants in the nineteenth century. Most heavy industry has now left the area, and the old factory buildings have been put to cultural use.

Canals and locks have been built to facilitate inland water traffic in the Lake District. The Vuoksi, Kymijoki, and Kokemäenjoki river basins contain a total of almost 40 locks and 30 open canals. The most extensive network of boating routes is in the Vuoksi basin, including nearly 600 km of 4.2-m deepwater channels, some 1,000 km of 2.4-m channels, and several hundred kilometers of 1.8- and 2.1-m channels. This network is also connected to the Baltic via Saimaa canal, making this, the EU's largest lake navigation area, important to Eastern Finland's economy.

Long-term monitoring of lakes has been conducted in Finland. The freezing and thawing of Kallavesi and Näsijärvi have been recorded since the 1830s; the water level in Lake Saimaa has been recorded daily since 1847. On some lakes, surface water temperatures and ice thickness have been monitored for nearly a century (Korhonen, 2002, 2005).

Lakes have slow currents that are very important to their ecosystems. Today's technology can determine a lake's flow field in great detail from the surface to the bottom; this is a sector in which Finnish researchers are at the forefront.

A map of the areal distribution of lakes in Finland is shown in [Figure 1](#); [Table 1](#) gives some characteristics of ten largest lakes.

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Cross-references

[Classification of Lakes from Hydrological Function Water Framework Directive](#)

FINNISH LAKES, TRENDS AND REGIONAL DIFFERENCES OF PHYTOPLANKTON

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Synonyms

Bacillariophyceae; Blue-green algae; Chlorophyceae; Cyanobacteria; Cyanophyceae; Diatoms; Green algae; Prokaryotic cyanobacteria

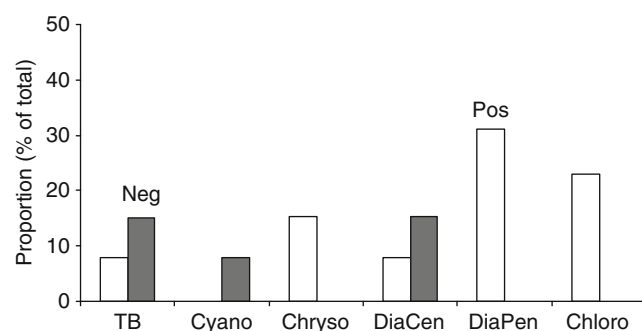
Definition

Phytoplankton – Free-living autotrophic and mixotrophic eukaryotic and prokaryotic cells.

Introduction

Lakes cover 10% of the area in Finland and the number of lakes with a surface area >100 km² is the highest in Europe. Similarly as in many other countries in Europe, also in Finland, major changes in nutrient loadings took place after the Second World War (Simola and Arvola, 2004). As a result, the ecological condition of many lakes deteriorated, and only since 1970s, the water quality of the lakes and rivers started slowly to improve due to wastewater treatment plants and thus a decline in sewage waters (Niemi et al., 2004). However, atmospheric deposition (especially nitrogen deposition) and loadings from agriculture have strongly increased since 1950s, and in many lakes, the load from agriculture has become the main source of nitrogen and phosphorus.

Besides eutrophication, in Finland, there are also regional differences in the background loading with more fertile soils on the coast of the Baltic Sea (Leka et al., 2008) than in areas further in North and East. In Northern and Eastern Finland, there is much less agriculture than in South, and landscape is even more dominated by forest and peatlands. Besides the bedrock and soil properties,



Finnish Lakes, Trends And Regional Differences of

Phytoplankton, Figure 1 A summary of statistically significant (Mann-Kendall) long-term trends of phytoplankton taxonomical groups in the study lakes. The proportion of total indicates the proportion of significant increasing (Pos) and/or decreasing (Neg) trends in lakes. *TB* Total phytoplankton biomass including cyanobacteria, *Cyano* Cyanobacteria, *Chryso* chrysophytes, *DiaCen* Centric diatoms, *DiaPen* Pennales diatoms, *Chloro* chlorophytes. White bars = increasing (pos) trends, gray bars = decreasing (neg) trends.

land use, atmospheric deposition, and climate explain the wide variation in nitrogen and phosphorus concentrations in Finnish lakes (e.g., Lepistö et al., 2006; Sippola and Yli-Halla, 2004).

In unproductive lakes in the northern temperate region, phytoplankton can be nitrogen limited rather than phosphorus limited (Rekolainen et al., 2004; Bergström et al., 2005; Bergström and Jansson, 2006; Weyhenmeyer et al., 2007), which is in conflict with the generally accepted concept of phosphorus-limitation in temperate lakes (Vollenweider, 1968; Dillon and Rigler, 1974; Schindler, 1977). In Finland, Pietiläinen and Räike (1999) and Räike et al. (2003) have earlier suggested, however, that in large lakes, phosphorus would be the limiting nutrient for phytoplankton.

In this chapter, long-term trends and regional differences in phytoplankton in 19 large Finnish lakes are reviewed. The study lakes represent 38% of the total number of large lakes (>100 km²) in Finland and they distribute from the South (61°) to the North (69°). The used data sets cover the uppermost 0–2 m of the water column and the summer season, i.e., June, July, and August. Samples for water chemistry and chlorophyll *a* were collected since 1980 and for phytoplankton since 1982. For more detailed information on the material and methods as well as results, see Arvola et al. (2010).

Trends in phytoplankton

Phytoplankton biomasses declined since the early 1980s in 15% of the study lakes (Figure 1). For diatoms, the trend is less consistent, however, because the biomasses of

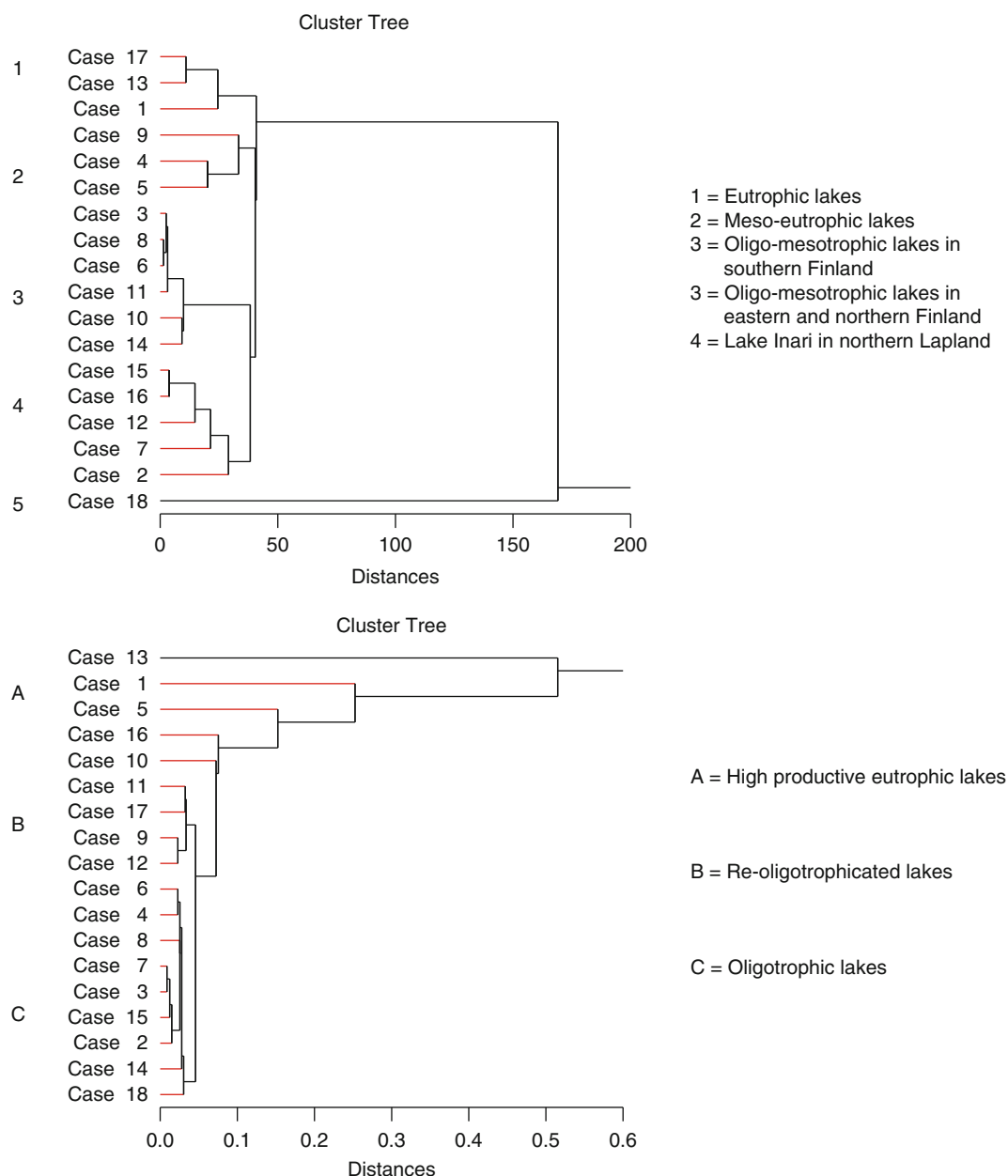
Finnish Lakes, Trends And Regional Differences of Phytoplankton, Table 1 The relationships (Pearson Product Moment correlation) between the total phytoplankton biomass and dominant algal groups and total phosphorus, total nitrogen and nitrate-nitrogen, and lake's northern and eastern position. The mean values for each lake were used in the calculations

		TP	TN	N:P	NO ₃	°N	°E
Total biomass	r	0.896	0.71	−0.568	−0.0888	−0.315	−0.546
	p	5.09E-07	0.000961	0.014	0.735	0.203	0.019
	n	18	18	18	17	18	18
Cyanobacteria	r	0.873	0.588	−0.522	−0.214	−0.368	−0.492
	p	2.33E-06	0.0103	0.0263	0.41	0.133	0.0381
	n	18	18	18	17	18	18
Chrysophyceae	r	0.736	0.62	−0.326	0.0442	−0.507	−0.384
	p	0.000496	0.00602	0.186	0.866	0.032	0.116
	n	18	18	18	17	18	18
Bacillariophyceae	r	0.602	0.555	−0.466	−0.103	−0.0947	−0.508
	p	0.00815	0.0169	0.0512	0.695	0.708	0.0315
	n	18	18	18	17	18	18
Centric	r	0.351	0.415	−0.341	−0.0447	0.0569	−0.39
	p	0.153	0.087	0.166	0.865	0.823	0.11
	n	18	18	18	17	18	18
Pennales	r	0.81	0.638	−0.546	−0.156	−0.26	−0.572
	p	4.53E-05	0.00436	0.0191	0.55	0.298	0.013
	n	18	18	18	17	18	18
Chlorophyceae	r	0.938	0.706	−0.508	−0.123	−0.473	−0.491
	p	9.1E-09	0.00107	0.0313	0.638	0.0475	0.0385
	n	18	18	18	17	18	18
Mean	r	0.78725	0.61725	−0.4555	−0.09895	−0.36068	−0.46875

centric diatoms have decreased in almost 15% of the lakes while the biomasses of Pennales diatoms have increased in nearly one third of the lakes. The share of green algae in the total phytoplankton biomass has also increased in a similar way to that of the Pennales diatoms, while in chlorophyll *a* an increasing trend was found in three lakes of 19 and a decreasing trend in two lakes. At the same time, total phosphorus (TP) concentrations declined

significantly ($p < 0.1$) in >40% and total nitrogen (TN) in >25% of the lakes.

The mean summer chlorophyll *a* concentration of the lakes correlated strongly with TP while the relationships between chlorophyll *a* and nitrate-nitrogen were not significant but a weak positive trend was observed in June. It seemed that TP and chlorophyll *a* concentrations follow each other closely in the study lakes irrespective of their



Finnish Lakes, Trends And Regional Differences of Phytoplankton, Figure 2 The study lakes classified by the clustering technique according to the (a) major nutrients and chlorophyll *a* concentrations, and (b) mean biomass of the most abundant taxonomical groups of algae (including cyanobacteria). The numbers represent the following lakes: 1 = Vesijärvi, 2 = Yli-Kitka, 3 = Saimaa, 4 = Päijänne, 5 = Säskylän Pyhäjärvi, 6 = Pyhäjärven Pyhäjärvi, 7 = Karjalan Pyhäjärvi, 8 = Pielinen, 9 = Näsijärvi, 10 = Oulujärvi, 11 = Längelmävesi, 12 = Lentua, 13 = Lappajärvi, 14 = Konnevesi, 15 = Koitere, 16 = Kemijärvi, 17 = Kallavesi, 18 = Inari.

geographical location or trophic. The regression between the biomass of algal groups and TP was highest for chlorophytes and Pennales diatoms, and lower for chrysophytes and centric diatoms (Table 1).

When the same procedure was used to cluster the lakes according to the biomasses of the major taxonomical groups of algae, cyanobacteria, chrysophytes, green algae, and diatoms, three major clusters were identified (Figure 2). The four lakes in group A consisted of relatively high productive lakes. The lakes in group (B) were more diverse but at least two of them have experienced re-oligotrophication. The lakes in the third group (C) consist of oligotrophic lakes, and most were situated in the East or the North. All the lakes in group A had total biomasses and cyanobacterial biomasses that were higher than in the lakes in the other groups while the share of chrysophytes was lower. A characteristic feature for the lakes in group C was the increased importance of chrysophytes which contributed, on average, 22–36% of the phytoplankton biomass.

Regional differences

In geographic terms, the nutrient concentrations decreased toward to the East and North and there was an associated decrease in the chlorophyll *a* values toward to the East. Toward the North, the decreasing trend of chlorophyll *a* was not significant, however.

When the lakes were subjected to a hierarchical cluster analysis according to their nitrogen and phosphorus concentrations, five lake groups were formed (Figure 2a). The first group consisted of the eutrophic lakes with highest nutrient concentrations. The second group consisted of meso-eutrophic lakes, while the third group included lakes situated in the southern part of the country and with a oligo-mesotrophic nutrient status. The fourth group consisted of lakes situating in the eastern and northern part of the country and with oligo-mesotrophic status. The “residual” group included only one lake in the far North with an ultra-oligotrophic status.

Summary

The chemical data clearly suggest that a systematic change in major nutrient (N, P) concentrations and the N:P ratio has taken place in Finnish large lakes, although in most lakes the rate of change has been relatively small as has also been shown by Pietiläinen and Räsänen (2001) and Niemi et al. (2004). Respectively, lower loading has resulted in lower phytoplankton biomasses in many lakes also during recent years in comparison to the early 1980s. Interestingly, the number of lakes where the biomasses have declined is lower than the number of lakes where the TP concentrations have declined which may indicate a delayed response in phytoplankton relative to the decreased nutrient loadings and concentrations (see Willén, 2001). Internal loading might be another reason for the delay. The long-term changes observed in the biomass of phytoplankton were

generally matched by the changes in the composition of the phytoplankton. The species and groups known to prefer oligotrophic conditions, such as the chrysophytes, were more abundant in oligotrophic lakes and those favoring eutrophic conditions, such as the cyanobacteria and particularly the order Chlorococcales green algae, were less abundant. These observations are in line with the results from other Nordic lakes (see Willén, 2001; Ptacnik et al., 2009).

Different algal species and taxonomical groups have their own physiological and ecological strategies and constraints (Reynolds, 1984), including nutrient preferences, which was clearly seen in the phytoplankton communities of lakes located in different regions. For example, the share of centric diatoms (Centrales) clearly increased from Southern to Northern Finland, i.e., from the higher nutrient concentrations to lower ones. Similarly, the share of pennate (Pennales) diatoms decreased from the West to the East, that is, from the higher nutrient concentrations to the lower ones (see Ptacnik et al., 2009). Thus, the proportion of two diatom groups with contrasting preferences to nutrient conditions showed quite a different regional distribution. Similarly, the share of chrysophytes has increased and the changes in the spatial distribution follow that of the Pennales diatoms. In contrast, cyanobacteria and particularly Chroococcales species were more abundant in lakes with higher nutrient concentrations. Major changes in the phytoplankton were observed in one third of the studied lakes. More importantly, such a clear geographical gradient in the phytoplankton from Southern to Northern and from Western to Eastern Finland has not previously been reported in the large Finnish lakes. These differences in the composition of the phytoplankton community clearly reflected the underlying differences in the major nutrients. This implies that nutrients seem to be the key driver for phytoplankton growth regardless of the lake's geographical location.

Several factors could account for the regional differences in the trophic status and phytoplankton of the large lakes in Finland. Among the most important are the soil type and its nutrient content, which in turn reflect the bedrock and the post-glacial history of the area. The recent land use in the catchment is also an important factor although this cannot be wholly separated from the soil type and bedrock. In general, the results reported from the Swedish large lakes by Willén (2001) are very similar with the limitation of phosphorus for phytoplankton and long-term reductions in the concentration of phosphorus and the biomass of phytoplankton.

In conclusion, long-term declines in TP and TN concentrations were found in nearly half of the lakes which also coincided with major changes in phytoplankton biomass. A clear regional gradient from Southern to Northern and from Western to Eastern Finland was observed in phytoplankton and nutrients. The role of phosphorus as the limiting nutrient was evident while the N:P ratio had a low value in predicting the occurrence of cyanobacteria.

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Cross-references

[Cyanobacteria \(Blue-Green Algae\)](#)
[Dissolved Oxygen in Ice-Covered Lakes](#)
[Finnish Lakes](#)
[Health Aspects of Lakes and Reservoirs](#)
[Ice Covered Lakes](#)
[Kis-Balaton and its Effect on Lake Balaton Water Quality](#)
[Light and Primary Production in Lakes](#)
[Nutrient Balance, Light, and Primary Production](#)
[Phosphor Exchange Sediment-Water](#)
[Võrtsjärv Lake in Estonia](#)

FLOODPLAIN WETLANDS: FOCUSING ON INDIA

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Synonyms

Back swamps; Delta plains; Levees; Oxbow lakes

Definition

Floodplain – flat land or low land bordering rivers that are subject to periodic flooding.

Alluvial – soils occur along watercourses occupying nearly all level areas subject to periodic flooding.

Introduction

A floodplain is a plain land formed along the course of a river by the deposition of sediment, typically dropped by a river during periodic floods. Any obstruction across a river's course, such as a band of hard rock, may form a floodplain behind it, and indeed anything that checks a river's course and causes it to drop its load will tend to form a floodplain. Floodplains are formed in two ways: by erosion and by aggradation. An erosional floodplain is created as a stream cuts deeper into its channel and laterally into its banks. Material is added to the floodplain during floods, a process called overbank deposition. The material that underlies floodplains is a mixture of thick layers of sand and thin layers of mud. Floodplains are neither static nor stable. Composed of unconsolidated sediments, they are rapidly eroded during floods and high flows of water, or they may be the site on which new layers of mud, sand, and silt are deposited. As such, the river may change its course and shift from one side of the floodplain to the other.

Floodplains can be looked at from several different perspectives. As a topographic category, it is quite flat and lies adjacent to a stream; geomorphologically, it is a land-form composed primarily of unconsolidated depositional material derived from sediments being transported by the related stream; hydrologically, it is best defined as a land-form subject to periodic flooding by a parent stream. A combination of these [characteristics] “Perhaps these perspectives may fulfill the essential criteria for defining the floodplain” (Schmudde, 1968). The characteristics and functions of a floodplain are intimately linked to the river that flows upon it. When unregulated, floodplains are highly dynamic like most fluvial landforms, and frequently inundated by overbank floods.

During high water events, some of the water is absorbed by the floodplain, helping to keep the river from overflowing. The absorbed water can then be returned to the stream during times of low water. If a high water event is large enough, water will overflow the channel of the river and flow onto and spread over the floodplain, which slows the flow of the water. Reduced water flow can help prevent severe erosion and flooding downstream. Floodplains are also home to many types of plants and animals and may also have forests and wetlands on or adjacent to them. These river edges provide habitat for insects, birds, reptiles, amphibians, and mammals. The vegetation also helps filter contaminants out of the water flowing into the river. Additionally, vegetated floodplains provide shade for the adjacent rivers and streams, increasing dissolved oxygen levels and consequently improving habitat for aquatic plants and animals.

Floodplains are most commonly found near the mouth of a large river, such as the Rhine, the Nile, or the Mississippi, where there are occasional floods and the river usually carries a large amount of sediment. Floodplains contain such features as levees (river embankments built by deposition as the river floods), backswamps, delta plains, and oxbow lakes. Rivers with extensive floodplains are the Nile, Ganges, Danube, and Po. People have been lured to floodplains since ancient times, first by the rich alluvial soil, later by the need for access to water supplies, recreation, etc.

The categorization of different varieties of wetlands into marshes, swamps, peat lands, and floodplain wetlands was first done by Maltby (1991). Investigations on various aspects of floodplain wetlands (Hoffmann, 1998) were mostly conducted during the past three decades only after the Ramsar Convention. However, knowledge about the characteristics and functioning of floodplain wetlands is important in order to restore and maintain them. Despite their importance, floodplain wetlands have been one of the least valued and most abused of world's natural resources today. These important wetland ecosystems are being exploited by the mankind for various activities, leading to degradation. Changes in climate and hydrology, blockage of floodplain flows, disposal of storm water, excessive grazing by native animals, agriculture and aquaculture practices, and recreational developments are some of the important causes of degradation.

Functions and values

Floodplain wetlands, in their natural state, have been cited to be of particular value since they have a high biodiversity, provide critical habitats for many plants and animals, and are an important, natural element in the maintenance of water quality (Mitsch and Gosselink, 1986; Whiting and Pomeroy, 1997; Takatert et al., 1999). Floodplain wetlands are essential to the maintenance of the hydrological, physical, and ecological health of our life support system – the riverine environment. They provide economic, social, and cultural benefits through their ability to enhance water quality, conserve flora and fauna, and mitigate floods, fishing and agricultural-related activities. The floodplain wetlands provide many recreational, educational, and scientific opportunities and add diversity to our landscape.

Floodplain wetlands of India

Floodplains and their associated wetlands are utilized by human beings throughout the world. Nowhere, this is truer than in Asia owing to high population density, thereby creating huge pressures on all forms of natural resources including the floodplain wetlands. India is naturally endowed with 0.2 million hectares of floodplain/oxbow lakes (*beels*) of which the state of Assam has the maximum number and the largest water spread area is mainly associated with the Brahmaputra and Barak river systems (Sugunan and Bhattacharya, 2000; Sugunan et al., 2000). The floodplain wetlands in India are an important resource for livelihood, both for rural and urban communities. These wetlands are widely distributed throughout the Eastern and Northeastern part of India under river Ganga and the Brahmaputra basins. Floodplain wetlands form the prime fishery resource in the states of Uttar Pradesh, Bihar, West Bengal, Assam, Manipur, Tripura, Arunachal Pradesh, and Meghalaya, where they are commonly known as beel, maun, tal, jheel, pat boar, chaur, etc.

Kaziranga National Park

Kaziranga National Park, the home of the great Indian one-horned Rhinoceros, is situated on the banks of Brahmaputra river (Figure 1). The terrain of the park comprises the floodplains of the Brahmaputra river, which is in general flat. The park area is bounded by latitude 26° 30'N and 26° 45'N and longitude 93° 05'E and 93° 40'E. It is one of the significant natural habitats for in situ conservation of biological biodiversity of universal value and included in the UNESCO World Heritage Site List in the year 1985. The Kaziranga National Park area consists of 429.93 km² with an additional area of 429.40 km² and situated in the two districts of Assam, namely, Golaghat and Nagaon.

Since Kaziranga area forms a part of the vast alluvial plains of the Brahmaputra river and its tributaries, the deposition of silt brought by these rivers during the rainy season each year gives rise to land masses getting stabilized over a period of time. The floodplain area of the



Floodplain Wetlands: Focusing on India, Figure 1 Satellite imagery of Kaziranga National Park, Assam, India, showing numerous floodplain wetlands and Brahmaputra river.

national park consists of a number of meander scars, wetlands, curvilinear streams, etc. A huge number of wild animals including one-horned rhinoceros (two-third of the world's great one-horned rhinoceros population) seek shelter in this park and the floodplain wetlands are the most favored habitat for one-horned rhinoceros. About 5.58% of the total area of the park is covered under floodplain wetlands locally known as "beels" during dry months. These wetlands ecosystems are highly productive and most important and significant natural habitats for in situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Although significant progress has been made in the conservation of the national park and its inhabitants, Kaziranga continues to face both natural and man-made challenges. Natural challenges include the flooding of vast areas of the forest during the long monsoons, which takes its toll on the animal population in particular the rhinoceros. The forest department has tried to address this in small measures by constructing several elevated land banks where animals can take refuge during floods. Conservation measures have also been implemented to arrest deforestation, soil erosion, etc., which deplete the area of its green cover. Recognizing the importance of its World Heritage Site status and global significance of this asset, the government has been dedicating increasing resources and working with international bodies to ensure that the Kaziranga National Park retains its distinctiveness as a vital global biodiversity hotspot and as a important floodplain wetland of national importance.

Summary

In the future, climate change may severely alter flood patterns over large regional scales. Consequently,

besides other anthropogenic factors, climate change represents a potential threat to river and associated floodplain ecosystems. The sustainable management of floodplain wetlands is an important issue and the policy makers should aim at research, planning, management, and education for adopting appropriate conservation measures.

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Cross-references

[Classification of Lakes from Hydrological Function](#)
[Deltaic Swamps](#)
[Everglades, Florida, USA](#)
[Lakes on Earth, Different Types](#)
[Wetlands](#)

FORTH AND CLYDE AND UNION SHIP CANALS, UK

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Definition

These busy canals in Central Scotland cross each other, the levels differing by 34 m.

The canals had been originally linked by 11 locks over a 1.5-km distance but these were dismantled in 1933. It was therefore considered to again link the two canals and a unique lift was devised, now known as the Falkirk Wheel, the world's first canal rotating boat-lift.

The Falkirk Wheel is located close to the Roman Fort at Rough Castle and to the best preserved section of the 55-km-long Antonine's Wall. Two boat "gondolas" on the end of curving arms balance each other so that the half rotation to change canal levels takes about 15 min with the

minimum of energy. The gondolas can take eight or more boats.

At the beginning of each cycle, each gondola will be at the level of one of the canals while boats enter and leave. The motors then turn the precisely balanced wheels through 180° and when each has come to rest the boats will be let out at the other canal level.

The process is aided by the use of Archimedes Principle whereby boats displace their own weight of water so that the tanks being full to the brim each boat that enters pushes out water that weighs exactly the same as the boat. The tanks therefore remain completely balanced.

The canals are fed by canal lochs, the largest being Cobbinshaw Loch south of Edinburgh

The Falkirk Wheel was opened by Her Majesty Queen Elizabeth II in 2002 and the Forth and Clyde Canal was considered, by the Institution of Civil Engineers and the American Society of Civil Engineers, an International Historic Civil Engineering Landmark, and a plaque in recognition of this accolade was erected by both institutions at the Falkirk Wheel in 2000.

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GENEVA LAKE

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Introduction

Lake Geneva (local name: Lac Léman; Lacus Lemanus in Roman times) is a large, crescent shaped, deep lake of glacial origin, located between Switzerland and France ([Figure 1](#)). It is the largest lake in Western Europe, and it consists of a deep eastern main basin and a small, shallow, narrow western basin, locally called Grand Lac (Great Lake) and Petit Lac (Small Lake), respectively. Physical characteristics of the lake are summarized in [Table 1](#).

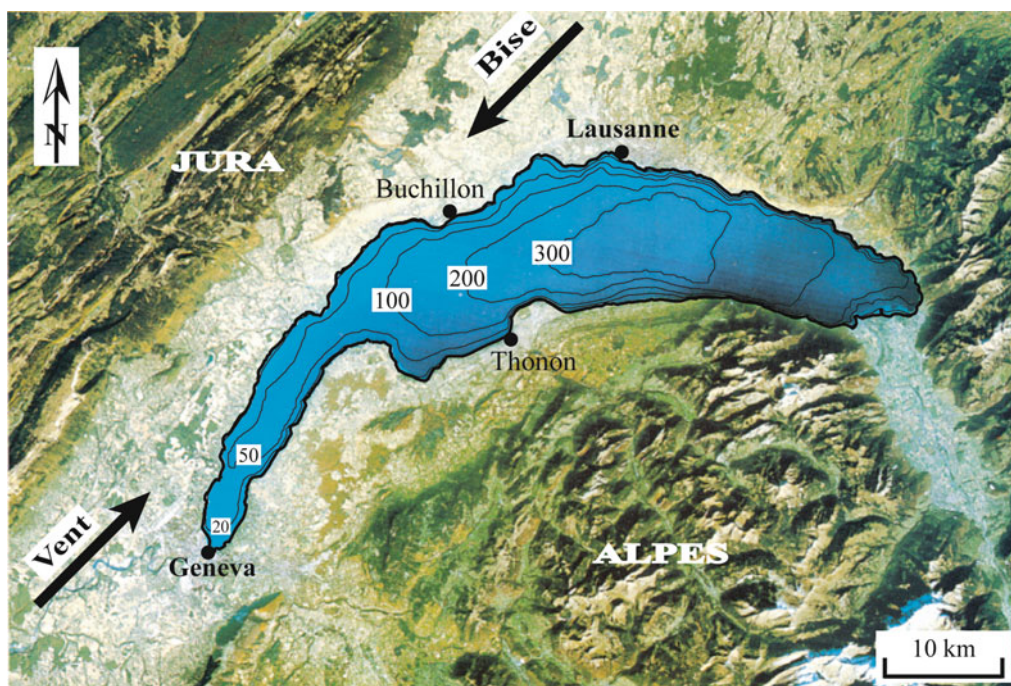
Lake Geneva is surrounded by the Jura Mountains to the northwest and by the Alps to the south. Most of the northern and western parts of the basin lie on a flat plateau. Steep alpine slopes, which rise to more than 1,000 m above the mean water level within 2 km of the shoreline, bound the lake basin to the east and southeast ([Figure 1](#)).

The main basin is characterized by a large bottom plateau in the center, limited by the 300-m isobath ([Figure 1](#)). A N-S cross section of the lake basin changes gradually from a U shape with steeply sloping sides and a bed material mainly composed of large boulders in the east, to a V shape with gentle slopes, mainly composed of fine sands, in the west.

Most of the catchment area is located in the Alps to the east and south of the lake basin with elevations up to 4,000 m. The ratio of the catchment area to the lake surface is 12.7, and snowmelt in the spring is an important process of water renewal. The main inflow to the lake is the river Rhone, which enters the basin from the east. The rivers Aubonne and Venoge, flowing down from the Jura Mountains in the north, and the alpine river Dranse in the south are secondary contributors to the hydraulic load. The only outflow from the lake is the Rhone river in Geneva at the western end of the lake, where the water level of the lake is controlled by a weir. In the water mass balance, river inflow and outflow clearly dominate over precipitation and evaporation, making Lake Geneva a fluvial lake with a theoretical residence time of about 12 years.

Climate, windfield, and thermodynamic state

Lake Geneva is situated in a temperate climate zone that is influenced by the Atlantic Ocean and the Mediterranean Sea. However, cold, dry air originating in the Siberian plains can make intrusions, mainly during the winter months. Monthly mean air temperature values range approximately from a minimum of 1°C in the winter to a maximum of 20°C in the summer. Annual mean air temperatures vary between 7°C and 12°C, with a long-term mean of 10.6°C. This has slightly increased over the past 30 years.



Geneva Lake, Figure 1 Satellite image showing Lake Geneva and the surrounding area. Main depth contours are shown. Arrows indicate mean wind directions.

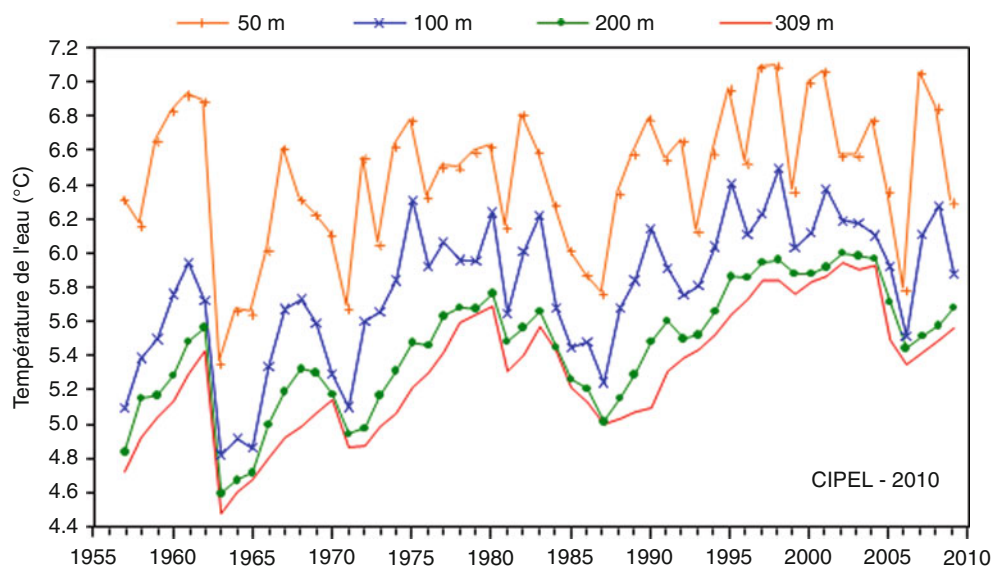
Geneva Lake, Table 1 Physical characteristics of Lake Geneva

Mean geographical coordinates	46°27'N 6°32'E
Elevation of mean water level	372 m
Maximum depth	309 m
Mean depth	152.7 m
Length along axis	72.3 km
Max. width	13.8 km
Length of shoreline	200 km
Surface Area Total	582 km ²
Great Lake (86%)	500 km ²
Small Lake (14%)	82 km ²
Volume Total	89 km ³
Great Lake (96%)	86 km ³
Small Lake (4%)	3 km ³
Drainage basin	6'380 km ²
Mean inflow	182 m ³ s ⁻¹
Mean outflow	250 m ³ s ⁻¹

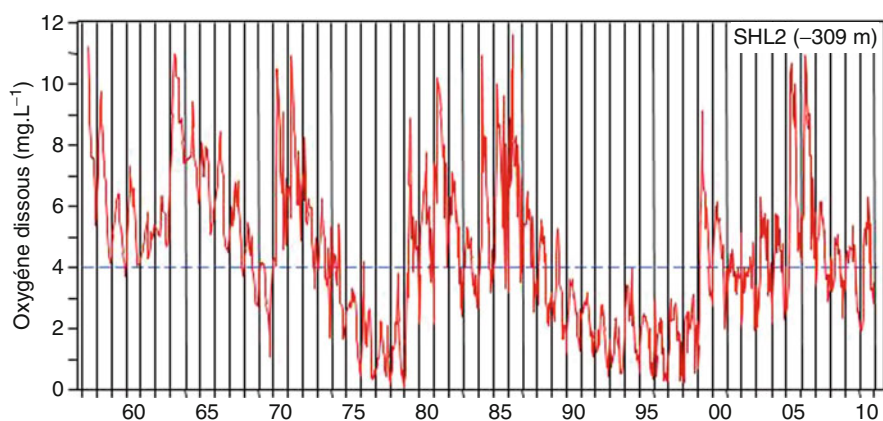
The windfield over the lake is strongly influenced by the local topography and is dominated by NE and SW winds, known by their local names as “Bise” and “Vent,” respectively (Figure 1). “Bise” winds are typically cold and dry, whereas “Vent” winds are warm and humid. Mean wind speeds are generally low; wind speeds greater than 5 ms⁻¹ are rare. They typically occur as short events and generate most of the water circulation in the lake.

Lake Geneva is a warm monomictic lake. It is strongly stratified throughout the summer season, with a thermocline developing at a depth of about 20 m. In the deep hypolimnion which has a thickness of more than 200 m, water temperatures change little as summer progresses. Cooler fall and winter air temperatures cause the thermocline to deepen and to gradually erode. Depending on the meteorological conditions in the winter, the lake may destratify at the end of the cooling period in late February, giving rise to homothermal conditions in the water column and cooling down to the bottom. However, this phenomenon is an exception. Typically, a weak stratification remains for several years, resulting in a saw-tooth pattern of deep water temperatures (Figure 2). This stratification pattern of the bottom water layers has a direct effect on the oxygen content of the hypolimnion (Figure 3) and thus on the biochemical cycle. A continuous increase of the mean annual air temperatures over the recent decades has caused annual mean temperatures to rise in the top (Figure 4) and bottom layers of the lake (Figure 2).

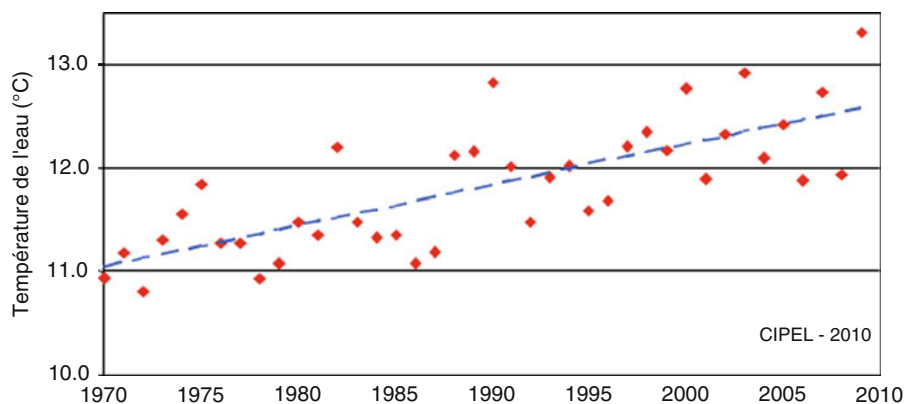
Due to the event structure of wind forcing, mean current circulation patterns in the lake are weakly developed. Currents in the upper-layer near-shore zone are the strongest, ranging from 5 to 20 cm⁻¹ for several days after wind events. On the central plateau at 309-m depth, current speeds vary from 3 to 7 cm⁻¹. Kelvin waves and Poincaré waves are strong contributors to the current field in the stratified lake.



Geneva Lake, Figure 2 Annual mean temperature in different layers at the deepest point of Lake Geneva (309 m) for the period 1956 to 2010. (Reproduced with authorization from CIPEL 2010).



Geneva Lake, Figure 3 Annual mean dissolved oxygen at the deepest point in Lake Geneva (309 m) for the period 1956 to 2010. (Reproduced with authorization from CIPEL 2010).



Geneva Lake, Figure 4 Annual mean temperature in the top 5 m at the deepest point of Lake Geneva (309 m) for the period 1956 to 2010. A linear trend is indicated by the dashed line. (Reproduced with authorization from CIPEL 2010).

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Cross-references

[Circulation Processes in Lakes](#)
[Climate Change Effects on Lakes](#)
[Europe, Lakes Review](#)
[Mixing in Lakes](#)
[Stratification in Lakes](#)
[Surface Seiches](#)
[Thermal Regime of Lakes](#)
[Water Balance of Lakes](#)

GIPPSLAND LAKES

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Introduction

The Gippsland Lakes of eastern Victoria, Australia, centered on 38°00' S, 147°30' E, comprise many interconnected lakes with a combined area of ca 400 km² (Bird, 1978). They are coastal lagoons enclosed from the sea by depositional barriers, but in the Australian context, they are big and permanent enough to be regarded as lakes. They owe their presence and form to a combination of geological, hydrological, and marine processes, and within the lagoons, wind-generated waves and currents, tidal and river currents, and ecological conditions have contributed to erosion and sedimentation.

The principal lakes from west to east are Lake Wellington (138 km², <4 m deep), Lake Victoria (110 km², up to 10 m deep), and Lake King (92 km², mainly <6 m deep but up to 15 m in a scour hole). Lakes Wellington and Victoria are connected by McLennan Strait, 12 km long and up to 11 m deep. The Latrobe and Avon Rivers empty into Lake Wellington, and the Mitchell and Tambo Rivers into Lake King. There are also three long, narrow, and shallow lakes adjacent to the coast from west to east: Lake Reeves, Bunga

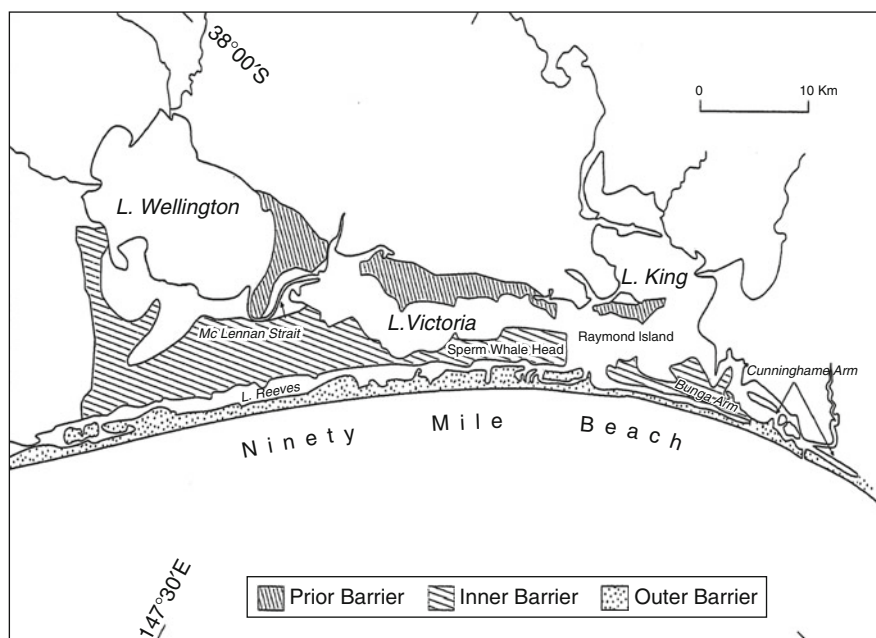
Arm, and Cunninghame Arm. The latter has an artificial opening to the sea, dating from 1889 which replaced a natural opening at the eastern end of the Arm that used to close periodically. The combined lakes have a catchment of 20,000 km² and lie in a mild, moist maritime climate. Annual rainfall of near 770 mm lacks seasonally, but annual evaporation of near 1,000 mm is strongly seasonal, so there is a deficit in summer/autumn. Salinity varies from almost fresh at times in Lake Wellington to seawater salinities at the entrance, with much of the system in the range 5–20 mg/L. Salinities are higher in summer than in winter and have increased since the entrance was artificially opened to the sea. Before this, the lakes often flooded in winter/spring and were almost fresh for a short period.

Fluctuations in lake levels are complex. Spring tides at the entrance to the lakes are about a meter, but tidal movements are soon dampened within the lake system. The eastern end of Lake King experiences tidal movements of 10 cm, while they are imperceptible westward of Lake King. Changes in atmospheric pressure change levels by a few centimeters, while wind-generated seiches along the west–east axes of the lakes can cause 60 cm variations and river floods can increase heights by up to 2 m for a few weeks. Together, these factors cause irregular changes in water level around the lake, no more apparent than McLennan Strait where there are unpredictable sharp alterations in current flow.

The shaping of the coastal embayment in which the Gippsland Lakes lie began in Tertiary times. The eastern highlands to the north were uplifted in the late Tertiary, and during the Pleistocene, there was further tectonic deformation along the Latrobe syncline which runs east–west and under Lake Wellington. During the Pleistocene and into the Holocene, there were numerous marine transgressions and regressions due to eustatic sea-level changes. A small tidal range combined with an abundant supply of sediments promoted the building of offshore barriers by refracted ocean swell. The dominant swell arrives parallel to the coastline, but there is sufficient refracted swell from the southwest to promote longshore drifting to the east.

Three partly overlapping barrier formations have been built. Each consists of beach ridges and swales parallel to the present beach alignment of Ninety Mile Beach (Figure 1) and widened by progradation on the seaward side. Parabolic dunes cross the parallel dunes in places, creating chaotic relief and swamps within the trailing arms. The earliest set of dunes, the Prior Barrier, formed against the old cliffed coastline near the river mouths and at a time when the sea level was about 2 m higher than present. It consists mainly of quartzose sands but with a significant component of reworked river gravels. Presently, it can be recognized on the northeast shore of Lake Wellington, beyond the northern shore of Lake Victoria and as Raymond Island in Lake King. Much of this initial barrier has been reworked both during low sea-level phases and along the present shores of the lakes, particularly Lake Victoria.

The inner barrier was formed to the seaward soon after the deposition of the prior barrier, firstly by growth of



Gippsland Lakes, Figure 1 Map of the Gippsland Lakes, Victoria, Australia, showing places mentioned in the text.

a spit from the western end and eventually as a series of old beaches across the mouth of the large embayment. It enclosed a narrow intervening lagoon, now Lake Victoria, which flooded out each end to large lagoons, now Lakes Wellington and King, respectively, with irregular shorelines abutting the drowned coastline. A series of parallel dunes developed from the beaches, each by aggradation seaward, and when the sea level was about 2 m higher than present. These dunes consist almost entirely of silicious sands that were deposited in earlier times on the seafloor.

Then followed a major drop in sea level which lasted from at least 75,000–20,000 years before the present. The lagoons were drained and the rivers entering them flowed across the dry floors, combining to enter the sea off the eastern end of Lake Victoria and near Sperm Whale Head, a prominent part of the inner barrier. During this time, large parabolics formed, particularly in the inner barrier, including Sperm Whale Head. The center of these dunes was blown out well below the present sea level and, today, is marked by swampy infills and small lagoons.

With the sea level rise in the early Holocene, largely completed 6,000 years ago, an outer barrier quickly formed in front of the inner barrier, so that the ocean swell hardly reached it. Again, it grew from the southwest and was incomplete for some time in the Sperm Whale Head area. The barrier is best developed in the southwest with 13 closely spaced ridges and least developed in the east with only one ridge. There are recurvatures and old channels behind it, telling of stages in its growth. Also, it varies markedly in width in keeping with the joining of offshore islands and the recurvatures as the barrier grew. The outer barrier takes the same alignment across the larger embayment as the inner barrier and shallow

elongated lagoons (Lake Reeves, Bunga Arm) are trapped between them.

The lake shorelines have been modified by erosion and deposition, due largely to wind-driven wave and current action. Extensive deposition of riverine deposits and in situ organic materials has filled in the sheltered back waters and drowned valley arms, particularly in Lake Wellington, western Lake Victoria, and Lake King. These areas are still swampy, being at or near present lake levels, and are often inundated during flood inflows. Some (e.g., Tucker Lagoon) remain as open water, mainly to the south of Lake Wellington. Where lakes abutt sandy shorelines, sand is moved along the shore to form cusped headlands and spits. These occur in a regular pattern along the narrow Cunninghame Arm, where they are interpreted as initial stages of lake segmentation. This process is common in lakes with sandy shores in windy environments (Lees, 1989). The most obvious deposits, however, are the deltas of the main rivers. Most of these (Latrobe, Avon, and particularly the Tambo) open into exposed waters so that the deltas are cusped in form. However, the Mitchell delta has grown into protected waters of northwestern Lake King, so its sediments are not well dispersed and a finger delta has resulted. Its lower reaches are spectacular as it heads eastward across the lake under the influence of the prevailing westerly winds.

Some sedimentation is due to marine sands being washed into the lagoons. This has occurred mainly at the western end of the outer barrier where the sea rarely breaches the barrier and fans have developed partially across Lake Reeves. Also, there has been some redistribution of sands near the artificial entrance, though most of this is offshore in the form of a curved sand bar.

Though the cutting of the artificial entrance in 1889 stabilized lake levels and provided a permanent navigable pathway, it allowed lake salinities to increase. Before this event, most shorelines of the lakes were fringed with common reed (*Phragmites australis*) which not only promoted sedimentation but protected shores from wave action. *Phragmites* grows well in fresh and slightly brackish water but not in moderate salinities. With the increase in lake salinities, a large proportion of that protective vegetation has died, and about 75% of the shorelines of the lakes are eroding. In some places, up to 50 m of shore has been lost over 100 years. The Mitchell River delta is disintegrating despite the delivery of river sediments. By contrast, the Latrobe and Avon deltas in Lake Wellington, which is still almost fresh, are still growing, aided in part by the greater delivery of sediments due to modern agriculture.

The Gippsland Lakes are the best studied marine lagoons in Australia. Similar broad conditions characterize the numerous other marine inlets in western, southern, and eastern Australia, but there are interesting differences outlined by Bird (1967), Roy (1984), Timms (1992), and Kidd and Timms (2000).

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Cross-references

[Australia, Climate and Lakes](#)
[Australia, Coastal Paleolakes of “Swanland”](#)

GLACIER JÖKULHLAUP

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Definition

A jökulhlaup is an Icelandic word for a glacier outburst flood that has been adopted by the English language and is now used to describe any large and abrupt release of water from a subglacial or proglacial lake/reservoir.

Vatnajökull, Iceland, is the most famous source of jökulhlaups (Björnsson, 2003), especially the *Grímsvötn* caldera (geological term for a cauldron-like volcanic feature usually formed by the collapse of land following a volcanic eruption) (Björnsson, 2003) (Gudmundsson et al., 1995). The origin of the floods is water stored in a lake, dammed in by ice, that gives away and releases the impounded water in a sudden outburst (Johannesson, 2002). This can be due to lifting or braking of the ice dam or melting of a tunnel under the ice. The reason for the accumulation of water in the storage is often geothermal melting of ice or volcanic subglacial eruption, but accumulation in marginal lakes is also a known cause (Roberts et al., 2005). There is usually some kind of triggering mechanism that determines when the flood is released, this may be the lifting of the ice dam by water pressure, undermining of the ice dam by erosion (piping) or a combination of both, so the timing of the onset of the flood cannot be predicted accurately (Tweed, 2000). Jökulhlaups are more often than not, violent and life-threatening events that need to be monitored closely under disaster management.

Water accumulation

A geothermal area has a natural heat output that can typically be 1 MW/km²; this melts around 400,000 t/year. Hot springs, steam vents, and small volcanic eruptions can increase this figure tremendously. On top of that there may be inflow of melt water due to ablation of the glacier and groundwater flow through the subsoil under the glacier. In order to predict the accumulation process, complex hydrological and glaciological surveys are necessary. The bottom under the glacier and the thickness of the glacier itself has to be surveyed by echo soundings and topographical surveys (Björnsson, 1982). The subglacial watershed and the drainage channel network can be determined from this data (Etzelmueller and Björnsson, 2000). Snow- and ablation surveys have to be performed and mass balance of the glacier estimated. Then, the curves for the elevation versus area and storage volume of the reservoir have to be prepared and the change in reservoir storage pressure recorded. In this way, the jökulhlaup risk can be monitored and the civil defense authorities alerted in time.

Jökulhlaup hydraulics

The hydrograph of a jökulhlaup is typically triangular shaped. When it is melting of an ice tunnel that determines the flow rate, the maximum discharge will usually come late in the flood period. When the jökulhlaup has the character of a dam break flood, the maximum discharge comes early. In both cases, the maximum flood can be estimated if the baseline (time length) of the hydrograph is known. The flood will in both cases brake up the glacier margin and float numerous icebergs down the channel harassing roads, bridges, and all other obstacles in the channel. The area coverage of the flood itself can be determined

by the usual methods applied for dam break floods (Eliasson, 2008), provided the source hydrograph is known. The flood itself progresses down the channel network like a transitory flood (Eliasson et al., 2007). In practice, this means that the flood wave travels easily over dry land like a wall of water that can be several meters high; the velocity of the wall is so high that it cannot be outrun by animals or humans, very much like a tsunami that inundates a coast. The CFD (Computational Fluid Dynamics) models used in modeling the flood wave are usually two-dimensional models; they can be used to produce videos that show an aerial view of the flood wave as Figure 3 does. Such videos can be made to show the progression of the wave front, the velocity of it, the arial extent of the inundation (Alho et al., 2007), and the water depths. They are therefore a useful tool in planning civil protection tactics, rescue operations, and other parts of the disaster management plan.

Jökulhlaup statistics

The magnitude and frequency of jökulhlaups depends on the accumulation rate at the source and the reservoir characteristics. Climatically controlled jökulhlaups can be modeled and the cyclic frequency found (Ng and Liu, 2009) (Alho and Aaltonen, 2008). For volcanic jökulhlaups, statistical methods can be used to find the risk of having an event in the, e.g., next year or in another time period. It is not uncommon to find that the distribution of the time periods in between consecutive events is lognormally distributed (Eliasson et al., 2006). By building an appropriate stochastic model, the risk can be estimated. However, this risk will increase with time, so its magnitude will have to be updated regularly.

Occurrence of jökulhlaups

Prehistoric occurrences

Geological evidence of jökulhlaups can be found in almost every region that has been glaciated in prehistoric times. This is especially true for the last ice age in the northern hemisphere. The three best known examples in North America are firstly the Lake *Agassiz* that covered much of Manitoba, western Ontario, northern Minnesota, eastern North Dakota, and Saskatchewan; secondly Glacial Lake *Missoula* in western Montana; and thirdly Glacial Lake *Ojibway* in northern Ontario and Quebec, Canada. All three are responsible for tremendous outbursts in the period 13,000–8,000 BP. These events are all believed to have caused serious climatic impacts, e.g., the Younger Dryas climate period. However, there are many controversial theories about these flood events and their connection to serious climate changes, shifts in the Gulf Stream, deep sea formation in the North Atlantic, thermohaline circulation, and the Great Ocean Conveyor Belt. North Siberia is another region where geological evidence of similar floods has been unearthed (Carling et al., 2010); there are also reports from Scandinavia (Klingbjør, 2004).

Jökulhlaups in historical times

Today jökulhlaups occur in the regions where glaciers that are remnants of the last glaciation remain. Apart from Iceland, there are reports of jökulhlaups in, e.g., Antarctica (Peters et al., 2009), the Himalayas (Richardson and Reynolds, 2000), and northern Sweden (Klingbjør, 2004).

The hall of fame

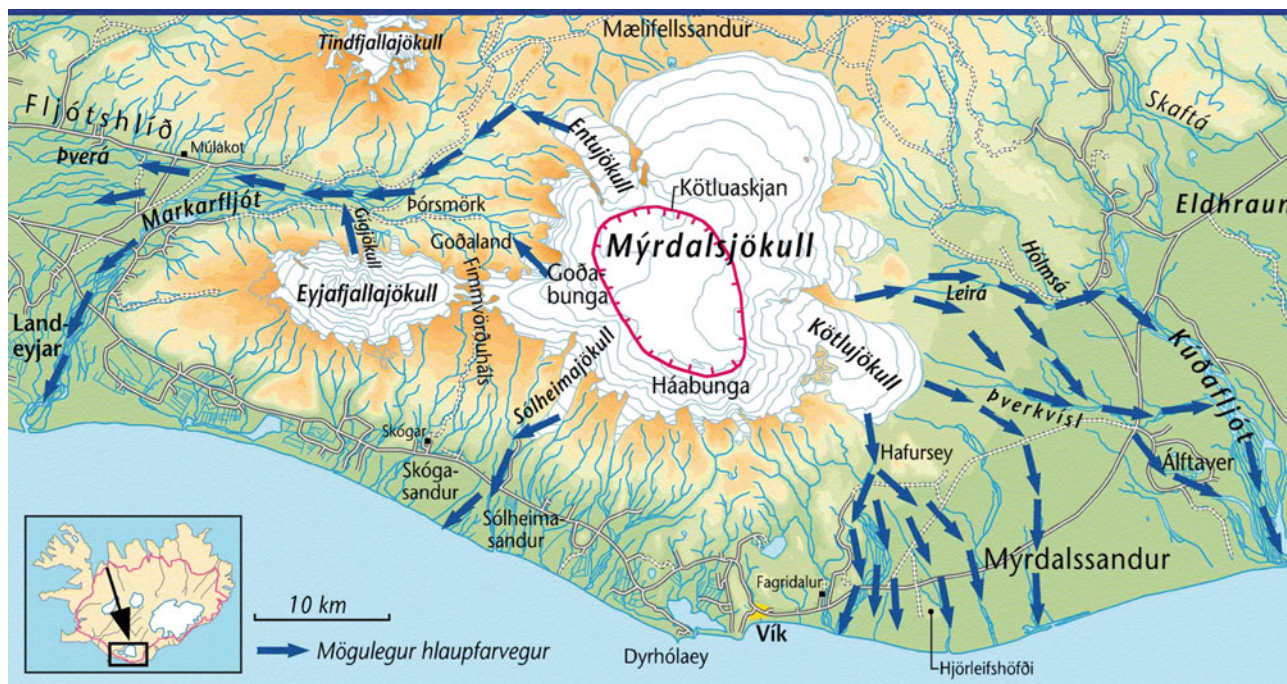
There are two jökulhlaup sites in Iceland that attract a lot of attention, and many reports exist on them. The course of a jökulhlaup event is best described by studying them.

The Katla system

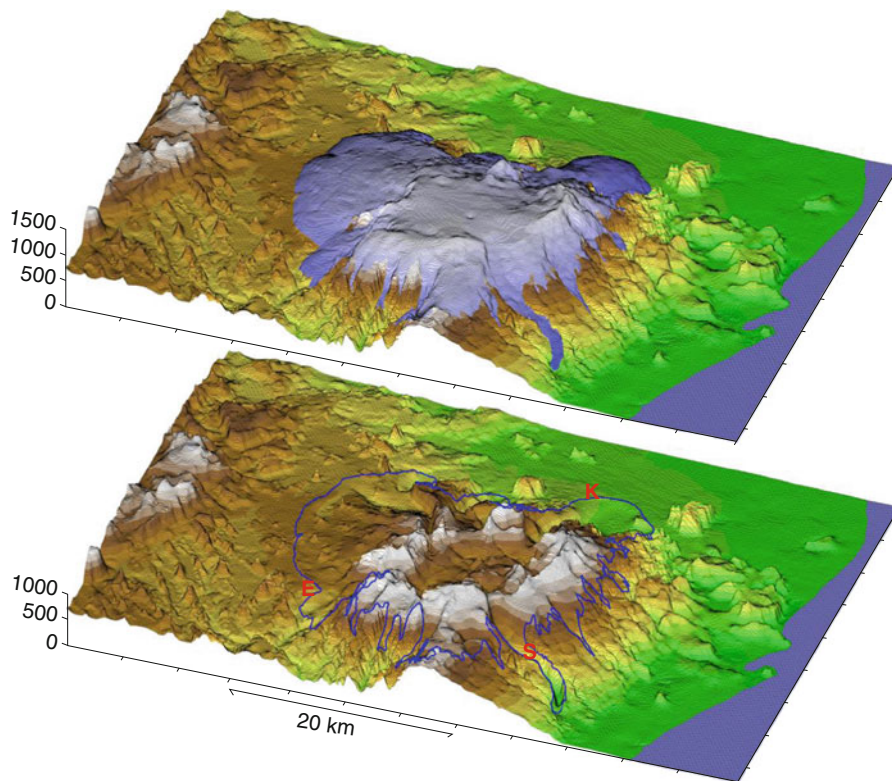
This is a 70-km³ caldera with associated flood channel system, located in *Mýrdalsjökull*, a glacier-covered mountain range in south Iceland, that reaches above an elevation of 1,500 m and is partly covered by the 200–700 m thick glacier which fills up a caldera and covers its eruptive vents. There are three volcanic craters under the glacier, one of them (*Kötlugjá*) has erupted regularly for the last 1,100 years. Geological evidence of earlier eruptions in the other two dates 6,000 years back in time. Katla jökulhlaups are exceptionally ferocious, sending a flood wave out to the sea that may reach a discharge of 300,000 m³/sand inundate the lowlands by up to 10 m of water. These jökulhlaups are by far the greatest floods experienced in the world in historical times; the last one occurred in 1918. It came from the easternmost volcano *Kötlugjá* (a little bit higher up than *Kötlujökull* in Figure 1). The other two are *Entujökull* just inside the westernmost rim of the caldera, and *Sólheimajökull* just inside the southwest rim of the caldera (Figure 1).

When there is an eruption, the ice over the crater is likely to be 400 m thick. The erupted mass has a temperature of 1,100–1,300°C, melts the ice very rapidly, and forms a cavity inside the glacier. Eventually the roof of the cavity will cave in, the eruption will reach above the water surface, and an eruption column will rise to a height of the order of magnitude 10 km and send volcanic ash and gasses into the atmosphere, causing significant poisoning of the air and all waters downwind of the eruption. Traces of gas and fine ash can be noticed many hundreds of kilometers away. Disruption of air traffic can be very severe; the Eyjafjallajökull event in April 2010 caused an economic loss of \$5 billion. The associated small jökulhlaup is marked by a blue arrow on Figure 1; it came from *Gígjökull*.

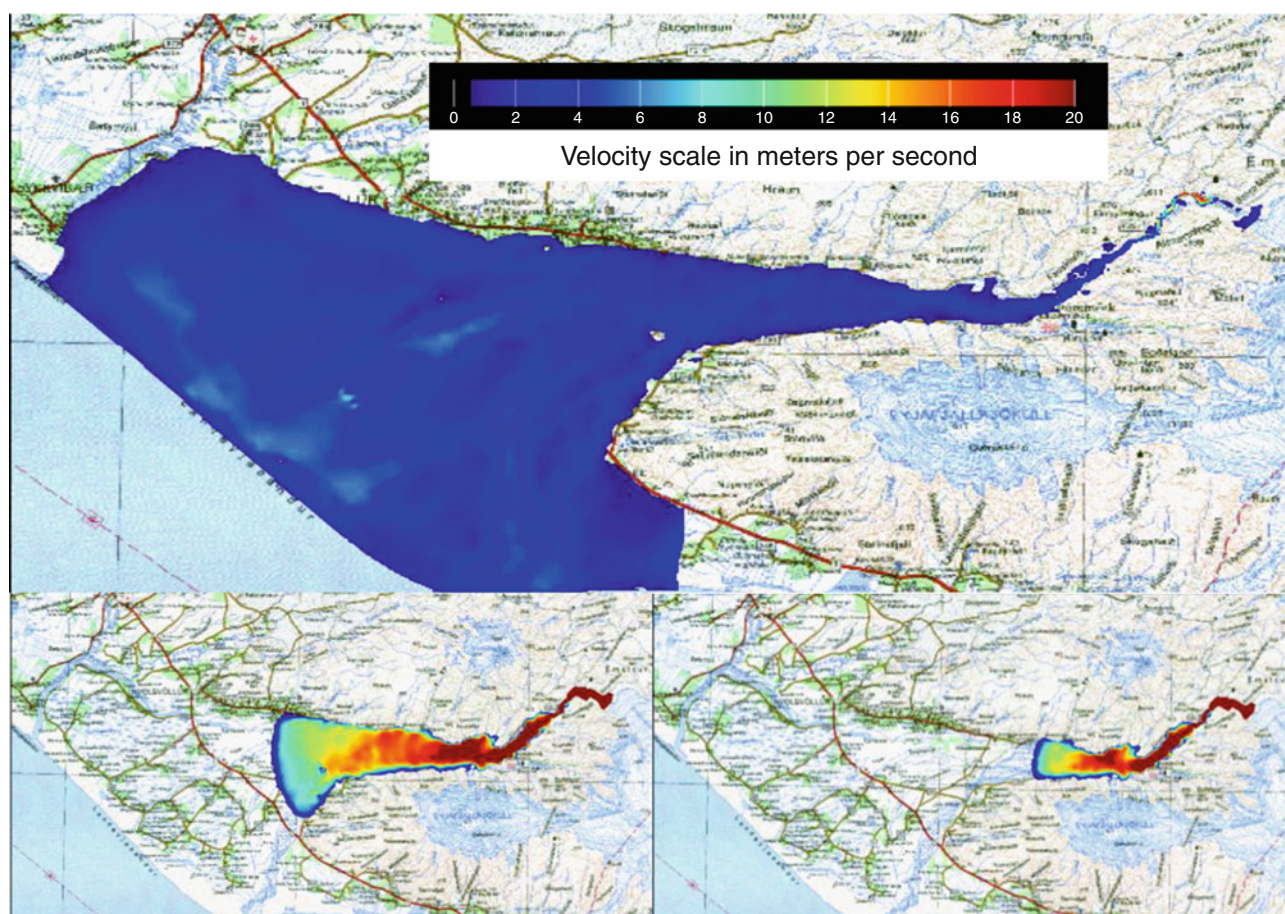
Figure 2 shows the results of the mapping techniques used in the investigations of jökulhlaups. The figure shows that in order to flow out of the caldera depression, the water has to flow over a threshold in pass carved in the mountain range by the glaciers. There are other passes that could be outlets, but the three outlets have the lowest thresholds. When the water flows over the thresholds, it breaks up the glacier in the channel and carries it as icebergs downstream. This combination of fast water flow and icebergs that can reach hundreds of tons is the reason for how destructive these floods are. They also carry a lot



Glacier Jökulhlaup, Figure 1 Mýrdalsjökull with the caldera Kötluaskjan (red), flood channels (blue) from the three volcanos (Copyright: Morgunblaðið newspaper).



Glacier Jökulhlaup, Figure 2 The Katla caldera with (top) and without (bottom) the glacier. The three outlet channels are shown (Echo sounding, mapping, and graphics by Helgi Björnsson, Finnur Pálsson, and Magnús T. Guðmundsson (2000)).



Glacier Jökulhlaup, Figure 3 Numerical simulation of the Entujökull jökulhlaup. *Top:* 9 h 13 min from the beginning of the event. *Bottom left:* 3 h 40 min. *Bottom right:* 2 h 00 min.

of pumice, sand, and gravel that by time form an alluvial plain, an example is seen on [Figure 3](#).

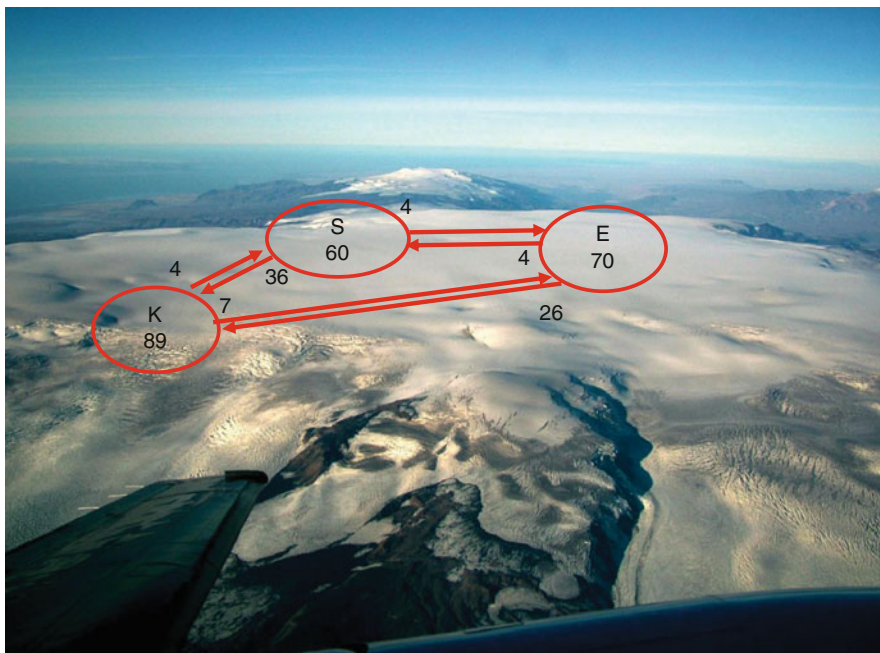
Several hundred people are living in the area, many more in the summer than in winter time. Numerical simulation is used to find the area inundated by the flood ([Figure 3](#)) in order to define the risk area. The Mýrdalsjökull is kept under close surveillance by the civil protection service; the rivers from the three glaciers are monitored for sudden flow augmentations and changes in chemical content, mainly hydrogen sulfide as it is a well-known magmatic gas. Seismicity is monitored as volcanic eruptions are preceded by earthquakes. There are however numerous earthquakes without any eruption, so the possibility of a false alarm is high ([Figure 4](#)).

The most dangerous flood wave is one in the west; the last one happened in 750 AD. Several hundred people live in the inundation area. These floods come with an average return period of 1000 years. The last eruption in 1918 was a big flood that occurred in the Kötlugjá (K). The overall average return based on the last 1,100 years of record is 50 years, so the probability for a flood in the

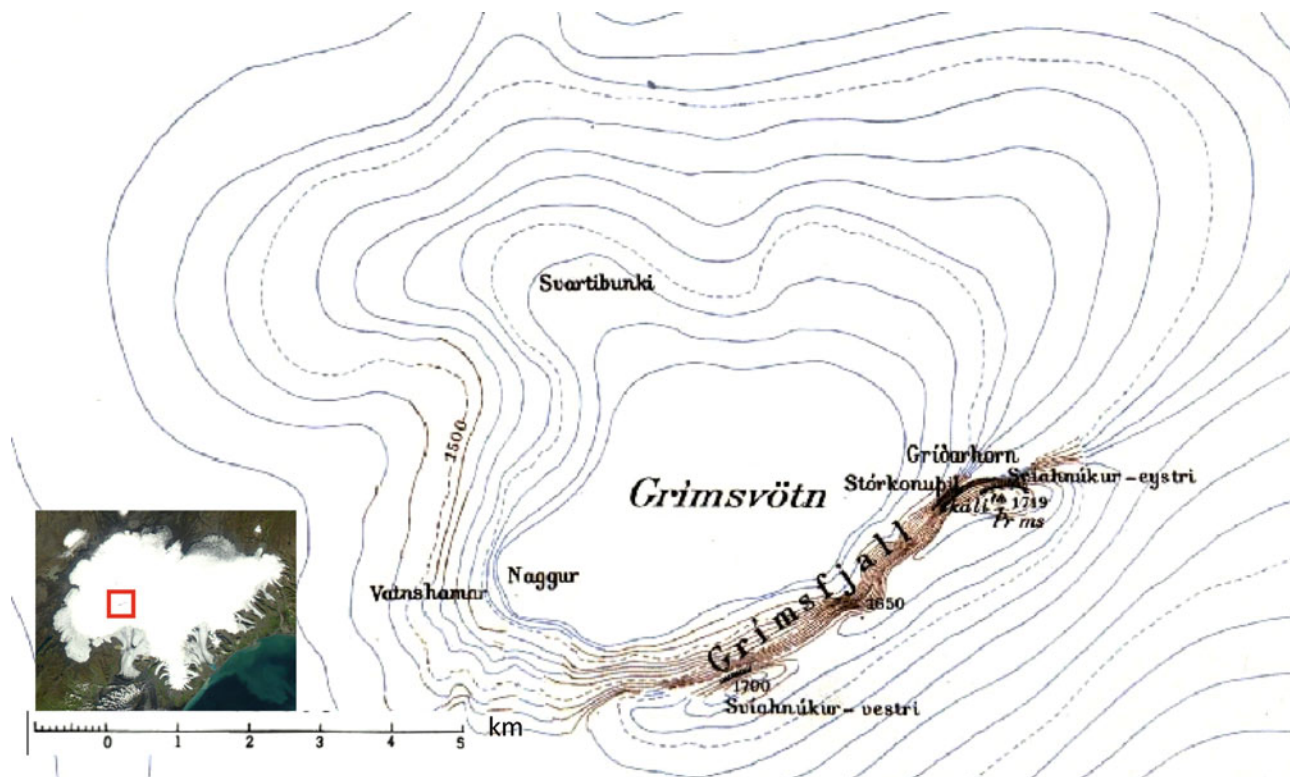
west is not very high. A long pause in the activity is likely when the last flood is as big as the 1918 event, and this complicates the statistics considerably, but it may be estimated that there is 50% probability for an eruption in the next 5 years. There are no reliable statistical estimates for the size of that eruption. Plans do exist for the evacuation of 2,000 people or more in a civil protection action when an eruption occurs.

The Grímsvötn-Skeidará system

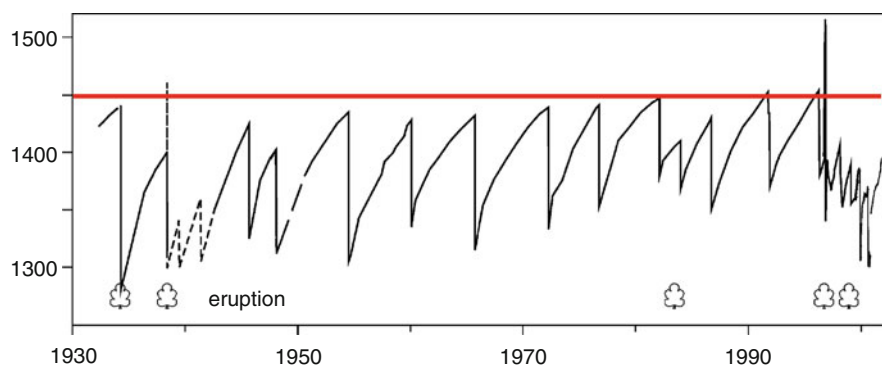
Water accumulates steadily in the Grímsvötn caldera ([Figure 5](#)). The ice sheet covering the water is for the most part 100–200 m thick and gets lifted up according to the accumulation rate. This rate depends on three factors, geothermal activity in the caldera and the watershed surrounding it, groundwater/iceflow/precipitation creeping and percolating in (a minor factor) and then the very uncertain factor, and volcanic eruptions inside the caldera or elsewhere in the watershed. The most famous event of this last type is the Gjálp eruption in 1996. This was an event outside the caldera bottom, but all the meltwater flowed into



Glacier Jökulhlaup, Figure 4 The position of the three volcanoes in Myrdalsjökull with eruption probabilities in%. Values in circles are the probability that the next eruption will be in the same place as the last one. Values near the beginning of an *arrow* indicate the probability the next eruption will occur in the crater where the *arrow* ends.



Glacier Jökulhlaup, Figure 5 Topographical map of the Grímsvötn caldera. Elevations in meters. Grímsvötn is an ice-covered lake that is the flat area in the calderas *bottom*. Location in Vatnajökull shown in the *left bottom* corner picture.



Glacier Jökulhlaup, Figure 6 Rise and fall of the surface of Grímsvötn 1930–2002. Elevation in meters above sea level on the left-hand scale. Red marker, 1,450 m (Bjornsson 2003).

the lake inside the caldera. Eruptions inside the caldera that do not melt any ice that is not already floating have very little effect on the uplift of the lakes' ice cover. When the water can start flowing over the threshold, a jökulhlaup is impending. This water flow is a combined action of the water pressure lifting the ice on the threshold up and the water eroding its way through the sediments on the bottom by piping over the last barrier. As may be seen on the map, the ice surface drops steeply on the other side of the mountain *Grímsfjall*, so when water reaches such a location with the full pressure head of the lake, it can easily lift up the glacier and flow on. This it does only slowly to begin with, but little by little it melts a tunnel over the threshold, so the discharge increases as time goes until the ice sheet settles on the bottom and the waterflow stops.

Figure 6 shows that during a jökulhlaup event, the ice cover sinks suddenly down on the order of magnitude 100 m and then rises slowly again. Before 1940, there are two large jökulhlaups influenced by volcanic eruptions. In 1970, there is a small eruption inside the caldera that causes the next jökulhlaup event to come sooner than expected, but apart from this, the process is fairly regular in 1940–1995 with an average return period of little less than 6 years. During this time, the maximum flood diminished and the flood period lengthened. The 1996 Gjálp eruption was a very large event as the volcanic eruption outside the caldera and higher up in the glacier sent large quantities of melt water into the caldera and caused the ice cover to lift so rapidly that the process did not have time to develop in the usual manner and resulted in a flash flood. This event has clearly altered the old mechanism, so the floods have an entirely different character since. The flood water flowing over the Grímsvötn threshold travels then downhill under the ice for about 50 km and emerges through a glacial port of Skeidará river in the easternmost side of the *Skeidarárjökull* margin and floods the sands from there to the sea. The 1996 flood that reached a peak of 40,000 m³/s ruined three bridges and several hundred meters of road, but otherwise these floods do little damage in spite of the fact that the normal discharge of Skeidará is

multiplied and the floods carry with them a very high quantity of sand, gravel, and icebergs.

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Cross-references

[Icelandic Lakes, Physical Characteristics](#)

GREAT LAKE PROCESSES: THERMAL STRUCTURE, CIRCULATION AND TURBULENT DIFFUSION PROCESSES

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Introduction

The Laurentian Great Lakes Basin is located along the international boundary between Canada and the United States. In extent the basin encompasses an area of 772,053 km². The Great Lakes comprise the largest volume of freshwater on earth. The system is comprised of five major lakes: Lake Superior, Michigan, Huron, Erie, and Ontario, which together occupy nearly one third of the total basin area ([Figure 1](#)). Flow from headwaters at Lake Superior to the final outflow into the Atlantic Ocean is continuous; water is transported through various connecting channels. With horizontal scales of hundreds of kilometers, depth scales of 100 m, and a well-developed seasonal thermal stratification in the summer, the Laurentian Great Lakes of North America are host to many of the physical phenomena associated with the coastal oceans or inland seas. The closed nature of the Great Lakes basins provides an excellent opportunity to study the Great Lakes systems as model oceans.

Seasonal thermal structure of the Great Lakes

The thermal structure in the Great Lakes generally depends on the season because of the large annual variation of surface fluxes ([Boyce et al., 1989](#)). With the exception of smaller Lake St. Clair and shallow western basin of Lake Erie, the Great Lakes are thermally stratified during the summer months. There are regional differences through the Great Lakes basin; full stratification may not occur until August in Lake Superior, whereas Lake Erie may be stratified by late May. The major differences between the oceans and the Great Lakes is a consequence of the equation of state for freshwater that shows a maximum density at 4°C. Thus convective overturning occurs both in fall and spring, making the lakes dimictic. The spring thermal bar is discussed more in this volume, so it is not discussed further here.

As the 4°C isotherm disappears from the surface to the deeper mid-lake, the thermal stratification progresses over the lake. The intensity of wind-induced turbulence determines the level to which the heat from solar radiation is mixed down, and hence, the thermocline tends to deepen during stormy periods. Isotherms drawn from a Lake Ontario model simulation is shown in [Figure 2](#). Surface heat losses and deep vertical mixing associated with large storms in the fall, result in the deepening of thermocline. A fall/winter thermal bar is noted on some occasions in the Great Lakes, followed by the coldest temperatures in February to early March in most of the Great Lakes.

Wind-driven circulation

The Great Lakes have complex velocity and scalar fields with a wide spectrum of dynamically important length scales ranging from circulation patterns of scales of 100 km down to small-scale turbulence of the order of millimeters. Superimposed on a mean flow circulation, these turbulent eddy-like motions exist in both horizontal and vertical directions. The scales of horizontal eddies, however, are much larger than those of vertical eddies because in the Great Lakes horizontal dimensions are greater than vertical dimensions. The Great Lakes manifest into two distinct flow environments: an open lake environment and a coastal environment. The main differences between these regions are that the momentum imparted by the wind stress is balanced by bottom friction inshore, while it is balanced by the Coriolis force offshore.

The prime driving force of circulation in the lakes is the wind ([Csanady, 1982](#)). [Betetsky et al. \(1999\)](#) compiled the mean circulation in the Great Lakes based on several experimental data sets conducted over the years ([Figure 3](#)). They noted that during the unstratified period (November–June), storm action is the most important forcing, as higher wind speeds and the absence of stratification allow the wind forcing to penetrate deeper into the water column. Storm-induced currents in the Great Lakes can be quite strong (up to several tens of cm/s), but the average (seasonal means) currents are rather weak throughout most seasons of the year (on the order of only a few cm/s). The average magnitude of summer circulation in the Great Lakes is 1.0–2.4 cm/s, while mean summer currents can be as small as 0.1 cm/s at certain locations and the maximum current speed can reach up to 7 cm/s. Currents typically change their direction with depth, and their speed decreases, which reflects the importance of baroclinic effects in the presence of the seasonal thermocline. The summer circulation pattern is mostly cyclonic in the upper Great Lakes, whereas the anticyclonic gyre dominates and only a smaller cyclonic gyre is present in the western part in Lake Erie. In Lake Ontario the cyclonic circulation in the central part is a dominant feature with stronger eastward current near the south shore. The Keweenaw current is a persistent feature of summer circulation in Lake Superior. Cyclonic circulation persists in the winter. Winter currents are generally



Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes, Figure 1 A map of the Laurentian (North American) Great Lakes.

stronger than summer currents, and, therefore, annual circulation patterns closely resemble winter circulation patterns.

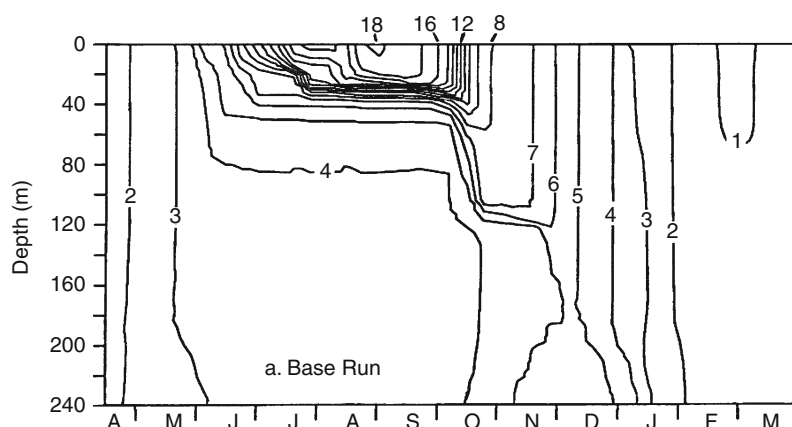
In the coastal regions, the wind action rapidly generates flow predominantly parallel to the coast. The coast prevents perpendicular movement, but longshore motion is unhindered and the longshore component of the wind is particularly effective in generating longshore currents and corresponding long particle displacements. However, winds at mid-latitudes are variable, rarely remaining constant for more than a day. Under these circumstances the transient properties of currents are often of greater practical importance than the steady state for constant wind. These transient properties depend on inertial forces.

Climatological aspects of coastal currents were developed in parts of Lake Ontario by employing carefully conducted field experiments. In general, the energy spectra of currents have broad peaks at around 10–12 days coinciding with basin scale response to meteorological forcing, and a spectral minimum at around 24–30 h. The dominant peak near 17 h corresponds to the near-inertial period of Lake Ontario, and increases in offshore

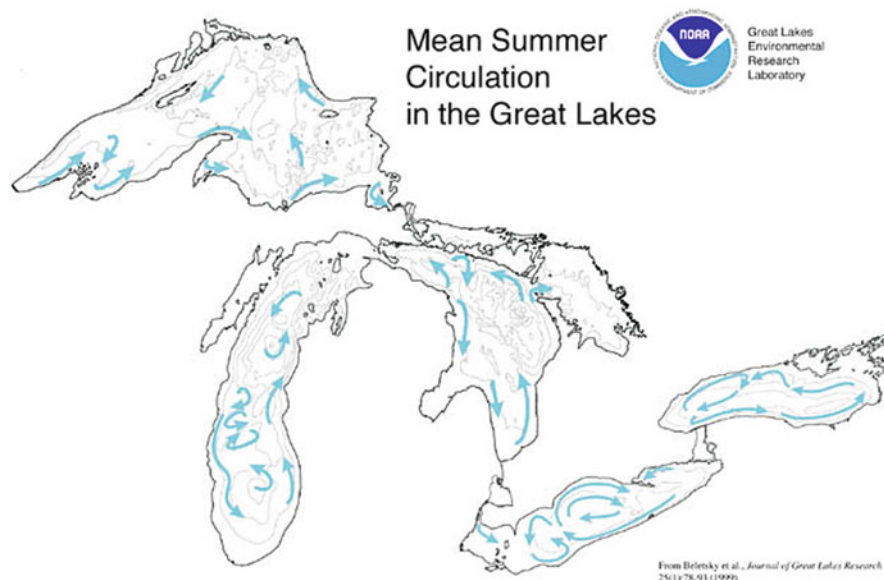
direction. The near-inertial oscillations, which are mainly due to large internal waves, are characteristic features of summer stratification and are observed to be intermittent in most of the lakes. The spectral minimum at 24–30 h was used for energy transfer from large-scale lake-wide circulation to small-scale oscillations for delineating mean flows and fluctuations. Also in the range of frequencies between Coriolis frequency and maximum Brunt-Vaisala frequency turbulent eddies are intermingled with near-inertial internal waves and the motions in this range are generally classified as mesoscale turbulent motions.

Horizontal diffusion

Horizontal exchange of heat, energy, and momentum occur at scales generally much larger than vertical exchanges, given the large horizontal lengths of natural basins compared to their depths. This has prompted many researchers to decouple horizontal transfers from vertical ones, even though horizontal and vertical processes interact. Numerous dye studies and tracer experiments conducted to determine the diffusion characteristics of the water column also show that the vertical exchange



Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes, Figure 2 Modeled annual cycle of vertical temperature structure in Lake Ontario.



Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes, Figure 3 Mean circulation in the Great Lakes (Source: Betetsky et al., 1999).

coefficient is much smaller than the horizontal counterparts. Here, we illustrate the nature of horizontal diffusion characteristics in the Great Lakes from a set of carefully conducted field experiments with (1) fluorescent dye studies (2) satellite tracked Lagrangian drifters, and (3) using point current meters or acoustic Doppler current profilers.

Tracer experiments

When a marked tracer is released into a turbulent environment such as oceanic coastal currents, the subsequent transport and diffusion of the tracer may be studied either in a frame of reference moving with the center of gravity of the plume or in a frame of reference fixed to the stationary source. Conventionally the former is referred to as

relative diffusion and the latter as absolute diffusion. The interlink between the two concepts is explained by the random movements of the center of gravity of the diffusing plume usually referred to as the meandering. One may regard absolute diffusion as a superposition of the two component processes of relative diffusion, i.e., diffusion relative to the center of gravity of the plume and meandering or bodily displacements of the diffusing plume parcels. In studies of turbulent diffusion in the natural environment, both formulations have been applied.

Experimental data from large-scale field diffusion studies in the Great Lakes have contributed a great deal to examine critically the dependence of the horizontal diffusion process on the properties of turbulent eddies.

Richardson's 4/3 power law has been the basis to interpret natural environmental diffusion data and results in view of the widely accepted physical basis on which it is derived by applying the concepts of the similarity theory of turbulence. In the inertial subrange the similarity theory predicts that the turbulent kinetic-energy spectrum $E(k)$ is given by the familiar $-5/3$ power law:

$$E(k) = c\varepsilon^{2/3}k^{-5/3} \quad (1)$$

where c is a universal dimensionless constant; ε is the rate of dissipation of turbulent kinetic energy, and k is the wave number.

We assume that turbulent eddies larger than the size of the diffusing cloud does not contribute much to the diffusion process. Furthermore, if we designate a length scale $\iota = k^{-1}$ to the eddies responsible for the diffusion of the cloud, then for a point source initially released into a turbulent medium consisting of a spectrum of eddies of several sizes, the turbulent kinetic energy available for diffusion of the cloud would be:

$$\overline{q^2} \propto \int_k^\infty \partial(k) dk \quad (2)$$

Combining (1) and (2) the turbulent velocity associated with length scale, ℓ , is given by:

$$\overline{q^2}^{1/2} = c\varepsilon^{1/3}\ell^{1/3} \quad (3)$$

Following mixing length arguments an effective horizontal diffusivity of the diffusion process can be defined by:

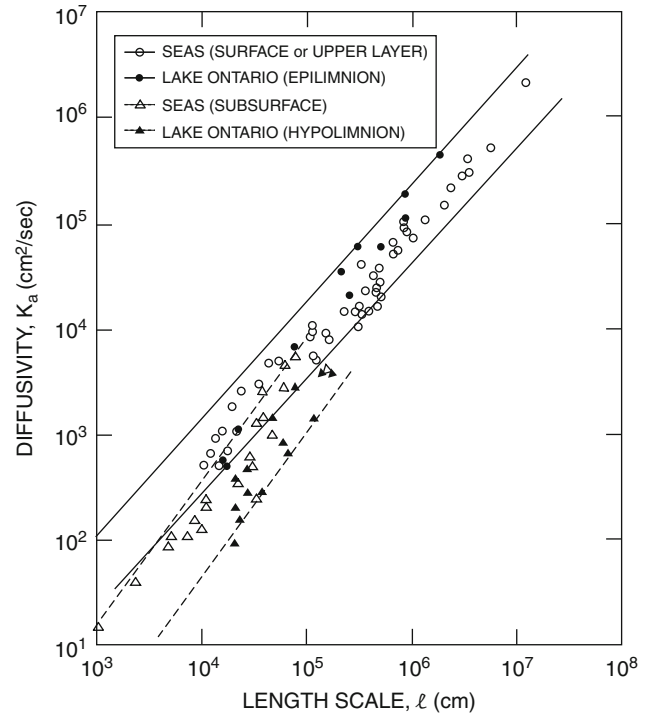
$$K = \text{const}\varepsilon^{1/3}\ell^{-4/3} \quad (4)$$

which is the Richardson's 4/3 power law of diffusion. The physical meaning of the Richardson's 4/3 power law is that the inertial subrange eddies are active and the diffusion process is characterized by two parameters: ε , the rate of turbulent energy dissipation and ℓ the length scale of eddies.

Experimental diffusion data from Lake Ontario and some parts of the oceans validate the Richardson's 4/3 power law of diffusion quite well. Figure 4 shows on logarithmic scale the effective diffusivity versus the length scale of diffusion from experimental diffusion data obtained in widely varying environmental conditions in the oceanic and aquatic environments (Murthy, 1976). The dependence of the effective diffusivity on the length scale provides useful guidelines for modeling of practical diffusion problems in the natural environment.

Lagrangian drifter experiments

Drifters have been used to study particle dispersion by oceanic turbulence since the early work of Stommel. Since that time drifter trajectories have been obtained for a wide



Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes, Figure 4 Horizontal eddy diffusivity as a function of length scale of diffusion field.

range of length and timescales. It quickly became apparent that eddy diffusion in oceans and lakes is not Fickian. Taylor (1921) showed that, in a stationary homogeneous turbulence, particle dispersion is related to Lagrangian integral timescales. In a study using drifter trajectories in an experiment conducted in Lake Ontario for two different flows, Lagrangian timescale, and eddy diffusion coefficients were calculated. The Lagrangian integral timescale (T_i^L) and length scale (L_i^L) are the time and distance over which the drifter motion remains correlated:

$$T_i^L = \int_0^T R_{ii}^L(\tau) d\tau \text{ and } L_i^L = \sqrt{\langle u_i'^2 \rangle} \int_0^T R_{ii}^L(\tau) d\tau. \quad (5)$$

Here, R_{ii}^L is the autocorrelation function defined as:

$$R_{ii}^L(\tau) = \frac{1}{T} \frac{\int_0^{T-\tau} u_i'(t) u_i'(t+\tau) dt}{\langle u_i'^2 \rangle} \quad (6)$$

where u' is the residual velocity defined by $u' = u - \langle u \rangle$, $\langle u \rangle$ denotes average over time. Further, it was observed that because of low-frequency motions, Lagrangian integral time and length scales are generally time dependent and do not approach a constant limit. Most of the individual autocorrelation functions oscillate and have significant

lobes, which underestimate the integral timescale as they are integrated over the duration of the time series. To avoid this, studies in the Great Lake integrate from zero to the time of first zero crossing.

By assuming that the drifter velocity fluctuations are homogeneous and stationary as a first-order approximation, we can write the mean squared dispersion due to single-particle motion as:

$$\langle x_i'^2 \rangle = 2 \langle u_i'^2 \rangle \int_0^t (t - \tau) R_{ii}^L(\tau) d\tau \quad (7)$$

When diffusion time elapses beyond some lag time t_ℓ (Lagrangian correlation timescale), $R_{ii}^L(\tau)$ will drop to zero. Physically t_ℓ is the decay timescale of those eddies which contributes to diffusion. Therefore, for large timescales $t > t_\ell$ the horizontal eddy exchange coefficient is given by:

$$K_i^L = \langle u_i'^2 \rangle T_i^L \quad (8)$$

Eulerian experiments

In a stationary and homogeneous turbulence, the Lagrangian variance $\langle u_L'^2 \rangle$ can be assumed to be equivalent to Eulerian variance $\langle u_e'^2 \rangle$. Hay and Pasquill (1959) pointed out that the essential difference between Eulerian and Lagrangian velocities is that, at a fixed point, velocity fluctuations appear to move rather quickly, as turbulent eddies are advected past the instrument. They have shown that the Lagrangian correlation function $R_{ii}^L(\tau)$ and the Eulerian counterpart $R_e(\tau)$ have a similar shape but differ only by a factor β , which is greater than unity: $R_e(\tau) = R_{ii}^L(\beta\tau)$. Introducing these assumptions, the horizontal exchange coefficient in terms of Eulerian statistics can be written as:

$$K_e = \beta \langle u_e'^2 \rangle T_e \quad (9)$$

where T_e is the Eulerian integral timescale.

The autocorrelations for Lagrangian and Eulerian currents showed a number of interesting features (Rao and Murthy, 2001). In Lake Ontario the autocorrelations of filtered Lagrangian velocities have fallen to near zero values for all drifters within 8–12 h, and have shown peaks at 14-h periodicity. The filtered Eulerian values showed a steady drop of alongshore autocorrelations, whereas cross-shore autocorrelations showed a peak at a period of 24 h. Lagrangian timescales (τ_L) estimated from autocorrelations were less than Eulerian timescales (τ_e). This was attributed to the affect of total acceleration in Lagrangian measurements which includes advection, whereas Eulerian timescales were only a function of local acceleration. This indicates the nonlinearity of the evolution of time-varying currents. In Great Lakes the value of $\beta = 1.4$ has been used to calculate Eulerian exchange coefficients. In general, alongshore exchange coefficients

(K_x) were slightly higher than cross-shore components (K_y) in the first 5.5 km from the shore. The cross-shore components reached a peak at around 6–7 km from shore and remained steady outside the coastal boundary layer. The studies in the Great Lakes indicate that momentum transfers occur in the longshore direction in the near coastal areas and cross-shore transfers may dominate in a zone where mid-lake motions adjust to shoreline. Although the magnitude of alongshore Lagrangian eddy coefficients were higher than Eulerian values, they showed a peak nearly at the same distance. The cross-shore exchange coefficients in the surface levels were in general lesser than subsurface values.

Vertical mixing

Several mechanisms such as current shear, breaking of internal waves, or convective overturns contribute to the generation of vertical turbulence in lakes and coastal oceans. The strong influence that the vertical shear and stability have on turbulence can be estimated from the gradient Richardson number, $Ri = N^2/S^2$. Here, N is the Brunt-Vaisala frequency given as $N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}$ and the vertical current shear $S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2$, where, z is the vertical coordinate positive upward, u and v are hourly cross-shore and alongshore currents, respectively, g is the acceleration due to gravity, and ρ_0 is reference density. Although, the turbulent mixing can be calculated on the basis of different models, simple models employing Richardson number have been quite popular in the Great Lakes.

In general, current shear in the upper mixed layer was closely related to the wind stress. In Lake Ontario during a full upwelling episode, N dropped to small values ($< 2.0 \times 10^{-2}$) and the vertical shear was weak all through the water column because of nearly homogeneous conditions. Because of low values of N , a weak current shear was sufficient to reduce Richardson numbers to near-critical values (< 0.25) in the upper mixed layer thus enhancing the turbulence. Part of this enhanced turbulence has resulted in increasing the vertical eddy viscosity coefficients ($30\text{--}40 \text{ cm}^2 \text{ s}^{-1}$) during this episode. On the other hand, downwelling episodes produced low N in the upper mixed layer, and much higher values in the bottom layers. This was due to a deepening of the mixed layer and the migration of thermocline close to the bottom. Vertical current shears slightly increased at a depth of 8–9 m at the base of the mixed layer. This slightly reduced the Richardson number and enhanced mixing at that level.

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Cross-references

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[Great Lakes, North America](#)

[Ladoga Lake and Onego Lake \(Lakes Ladozhskoye and Onezhskoye\)](#)

[Laurentian Great Lakes, Interaction of Coastal and Offshore Waters](#)

[Mixing in Lakes](#)

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GREAT LAKES, NORTH AMERICA

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Introduction

The Great Lakes – Superior, Michigan, Huron, Erie, and Ontario – are an important part of the physical and cultural heritage of North America. Spanning more than 1,200 km (750 miles) from west to east, these vast inland freshwater seas have provided water for consumption, transportation power, recreation, and a host of other uses ([Plate 1](#)).

The water of the lakes and the many resources of the Great Lakes basin have played a major role in the history and development of the USA and Canada. For the early European explorers and settlers, the lakes and their tributaries were the avenues for penetrating the continent, extracting valued resources, and carrying local products abroad. Now the Great Lakes basin is home to more than one-tenth of the population of the USA and one-quarter of the population of Canada. Some of the world's largest concentrations of industrial capacity are located in the Great Lakes region. Nearly 25% of the total Canadian agricultural production and 7% of the American production are located in the basin. The USA considers the Great Lakes a fourth seacoast, and the Great Lakes region is a dominant factor in the Canadian industrial economy.

Physical characteristics of the system

The magnitude of the Great Lakes water system is difficult to appreciate, even for those who live within the basin. The lakes contain about 23,000 km³ (5,500 cu. ml.) of water, covering a total area of 244,000 km² (94,000 square miles). The Great Lakes are the largest system of fresh, surface water on earth, containing roughly

18% of the world supply. Only the polar ice caps contain more fresh water ([Table 1](#)).

In spite of their large size, the Great Lakes are sensitive to the effects of a wide range of pollutants. The sources of pollution include the runoff of soils and farm chemicals from agricultural lands, the waste from cities, discharges from industrial areas, and leachate from disposal sites. The large surface area of the lakes also makes them vulnerable to direct atmospheric pollutants that fall with rain or snow and as dust on the lake surface.

Outflows from the Great Lakes are relatively small (less than 1% per year) in comparison with the total volume of water. Pollutants that enter the lakes – whether by direct discharge along the shores through tributaries, from land use, or from the atmosphere – are retained in the system and become more concentrated with time. Also pollutants remain in the system because of resuspension (or mixing back into the water) of sediment and cycling through biological food chains.

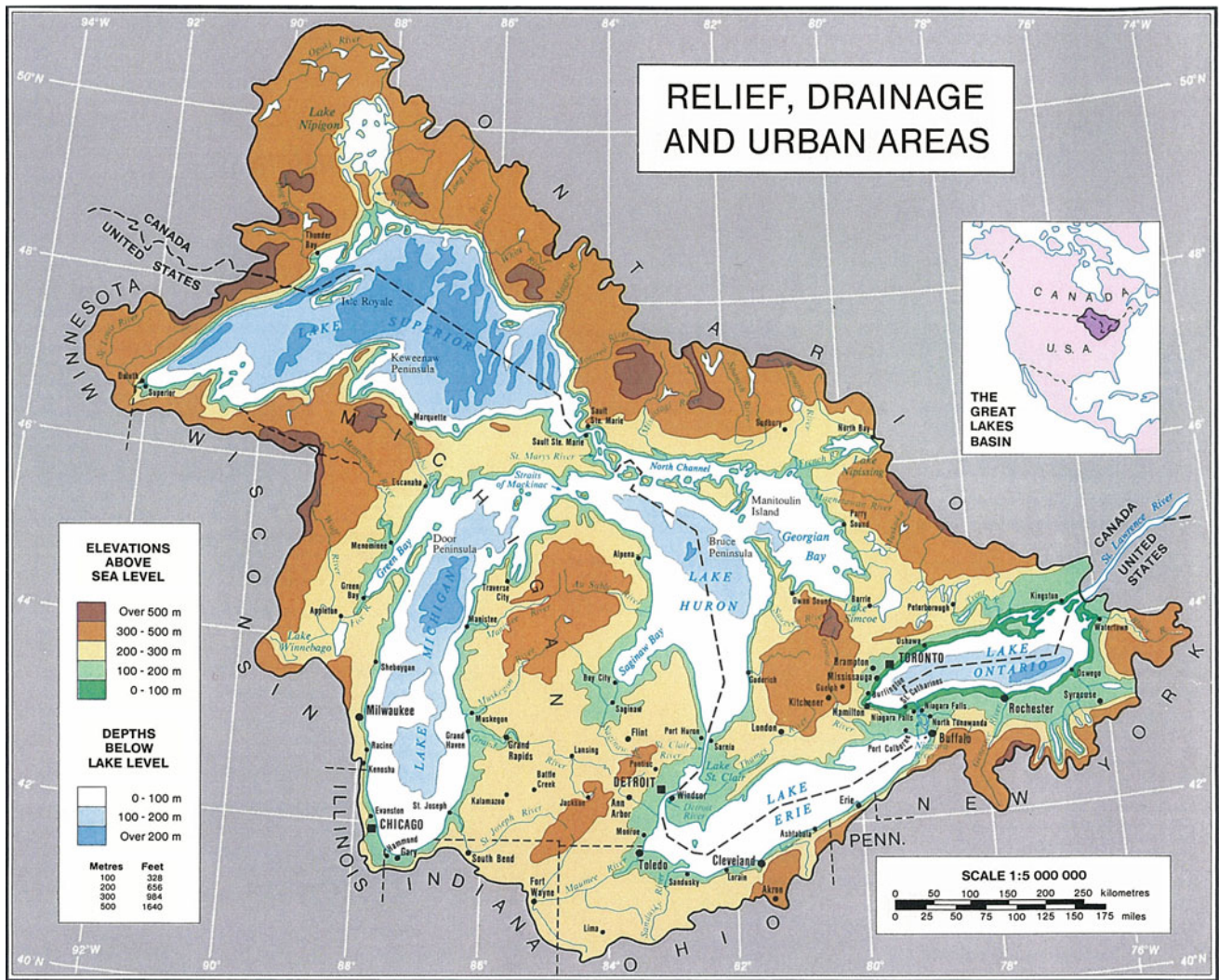
Because of the large size of the watershed, physical characteristics such as climate, soils, and topography vary across the basin. To the north, the climate is cold and the terrain is dominated by a granite bedrock called the Canadian (or Laurentian) Shield consisting of Precambrian rocks under a generally thin layer of acidic soils. Conifers dominate the northern forests.

In the southern areas of the basin, the climate is much warmer. The soils are deeper with layers or mixtures of clays, silts, sands, gravels, and boulders deposited as glacial drift or as glacial lake and river sediments. The lands are usually fertile and can be readily drained for agriculture. The original deciduous forests have given way to agriculture and sprawling urban development.

Although part of a single system, each lake is different. In volume, Lake Superior is the largest. It is also the deepest and coldest of the five. Superior could contain all the other Great Lakes and three more Lake Eries. Because of its size, Superior has a retention time of 191 years. Retention time is a measure based on the volume of water in the lake and the mean rate of outflow. Most of the Superior basin is forested, with little agriculture because of a cool climate and poor soils. The forests and sparse population result in relatively few pollutants entering Lake Superior, except through airborne transport.

Lake Michigan, the second largest, is the only Great Lake entirely within the USA. The northern part is in the colder, less developed upper Great Lakes region. It is sparsely populated, except for the Fox River Valley, which drains into Green Bay. This bay has one of the most productive Great Lakes fisheries but receives the wastes from the world's largest concentration of pulp and paper mills. The more temperate southern basin of Lake Michigan is among the most urbanized areas in the Great Lakes system. It contains the Milwaukee and Chicago metropolitan areas. This region is home to about eight million people or about one-fifth of the total population of the Great Lakes basin.

Lake Huron, which includes Georgian Bay, is the third largest of the lakes by volume. Many Canadians and



Great Lakes, North America, Plate 1 Michigan.

Americans own cottages on the shallow, sandy beaches of Huron and along the rocky shores of Georgian Bay. The Saginaw River basin is intensively farmed and contains the Flint–Saginaw–Bay City metropolitan areas. Saginaw Bay, like Green Bay, contains a very productive fishery.

Lake Erie is the smallest of the lakes in volume and is exposed to the greatest effects from urbanization and agriculture. Because of the fertile soils surrounding the lake, the area is intensively farmed. The lake receives runoff from the agricultural area of southwestern Ontario and parts of Ohio, Indiana and Michigan. Seventeen metropolitan areas with populations over 50,000 are located within the Lake Erie basin. Although the area of the lake is about 26,000 km² (10,000 square miles), the average depth is only about 19 m (62 ft), the shallowest of the five lakes, and therefore warms rapidly in the spring and summer and frequently freezes over in winter. It also has the shortest retention time of the lakes, 2.6 years. The western

basin, comprising about one-fifth of the lake, is very shallow with an average depth of 7.4 m (24 ft) and a maximum depth of 19 m and 62 ft.

Lake Ontario, although slightly smaller in area, is much deeper than its upstream neighbor, Lake Erie, with an average depth of 86 m (283 ft) and a retention time of about 6 years. Major urban industrial centers, such as Hamilton and Toronto, are located on its shore. The US shore is less urbanized and is not intensively farmed, except for a narrow band along the lake.

Settlement

The modern history of the Great Lakes region, from discovery and settlement by European immigrants to the present day, can be viewed not only as a progression of intensifying use of a vast natural resource but also as a process of learning about the Great Lakes ecosystem. At first, it was a matter of making use of the natural

Great Lakes, North America, Table 1 Physical features and population

		Superior	Michigan	Huron	Erie	Ontario	Totals
<i>Elevation</i>	(feet) ^b	600	577	577	569	243	
	(meters)	183	176	176	173	74	
<i>Length</i>	(miles) ^a	350	307	206	241	193	
	(kilometers)	563	494	332	388	311	
<i>Breadth</i>	(miles) ^a	160	118	183	57	53	
	(kilometers)	257	190	245	92	85	
<i>Average depth</i>	(feet) ^b	483	279	195	62	283	
	(meters)	147	85	59	19	86	
<i>Maximum depth</i>	(feet) ^a	1,332	925	750	210	802	
	(meters)	406	282	229	64	244	
<i>Volume^d</i>	(cubic miles) ^a	2,900	1,180	850	116	393	5,439
	(km ³)	12,100	4,920	3,540	484	1,640	22,684
<i>Area</i>							
<i>Water</i>	(sq. miles) ^a	31,700	22,300	23,000	9,910	7,340	94,250
	(km ²)	82,100	57,800	59,600	25,700	18,960	244,160
<i>Land Drainage Area^e</i>	(sq. miles) ^a	49,300	45,600	51,700	30,140	24,720	201,460
	(km ²)	127,700	118,000	134,100	78,000	64,030	521,830
<i>Total</i>	(sq. miles)	81,000	67,900	74,700	40,050	32,060	295,710
	(km ²)	209,800	175,800	193,700	103,700	82,990	765,990
<i>Shoreline Length^f</i>	(miles) ^a	2,726	1,638	3,827	871	712	10,210 ^g
	(kilometers)	4,385	2,633	6,157	1,402	1,146	17,017 ^g
<i>Retention Time (years)^b</i>		191	99	22	2.6	6	
<i>Population: USA (1990)^c</i>		425,548	10,057,026	1,502,687	10,017,530	2,704,284	24,707,075
<i>Canada (1991)</i>		181,573			1,664,639	5,446,611	8,484,290
<i>Totals</i>		607,121	10,057,026	2,694,154	11,682,169	8,150,895	33,191,365
<i>Outlet</i>		St. Marys River	Straits of Mackinac	St. Clair River	Niagara River Welland Canal	St. Lawrence River	

Sources:

^aCoordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, COORDINATED GREAT LAKES PHYSICAL DATA. May, 1992

^bEXTENSION BULLETINS E-1866-70, Michigan Sea Grant College Program, Cooperative Extension Service, Michigan State University, E. Lansing, Michigan, 1985

^c1990–1991 population census data were collected on different watershed boundaries and are not directly comparable to previous years

^dMeasured at low water datum

^eLand drainage area for Lake Huron includes St. Marys River; Lake Erie includes the St. Clair–Detroit system; Lake Ontario includes the Niagara River

^fIncluding islands

^gThese totals are greater than the sum of the shoreline length for the lakes because they include the connecting channels (excluding the St. Lawrence River)

resources of the basin while avoiding its dangers. Not until much later, when the watershed was more intensively settled and exploited, was it learned that abuse of the waters and the basin could result in great damage to the entire system.

Exploitation

The first Europeans found a relatively stable ecosystem which had evolved during the 10,000 years since the retreat of the last glacier; a system that was only moderately disturbed by the hunting and agricultural activities of the native peoples. The first European arrivals had a modest impact on the system limited to the exploitation of some fur-bearing animals. However, the following waves of immigrants logged, farmed, and fished commercially in the region, bringing about profound ecological changes. The mature forests were clear-cut from the

watersheds, soil was laid bare by the plow, and the undisturbed fish population were harvested indiscriminately by an awesome new predator – humans with nets.

As settlement and exploitation intensified, portions of the system were drastically changed. Logging removed protective shade from streams and left them blocked with debris. Sawmills left streams and embayments clogged with sawdust. When the land was plowed for farming, the exposed soils were washed away more readily, burying valuable stream and river mouth habitats. Exploitive fishing began to reduce the seemingly endless abundance of fish stocks, and whole populations of fish began to disappear.

Industrialization

Industrialization followed close behind agrarian settlement, and the virtually untreated wastes of early industrialization

degraded one river after another. The growing urbanization that accompanied industrial development added to the degradation of water quality, creating nuisance conditions such as bacterial contamination, putrescence, and floating debris in rivers and nearshore areas. In some situations, the resulting contaminated drinking water and polluted beaches contributed to fatal human epidemics of water-borne diseases such as typhoid fever. Nonetheless, the problems were perceived as being local in nature.

As industrialization progressed, and as agriculture intensified after the turn of the twentieth century, new chemical substances came into use, such as PCBs (polychlorinated biphenyls) in the 1920s and DDT (dichloro-diphenyl-trichloroethane) in the 1940s. Non-organic fertilizers were used to enrich the already fertile soils to enhance production. The combination of synthetic fertilizers, existing sources of nutrient-rich organic pollutants, such as untreated human wastes from cities, and phosphate detergents caused an acceleration of biological production (eutrophication) in the lakes.

In the 1950s, Lake Erie showed the first evidence of lake-wide eutrophic imbalance with massive algal blooms and the depletion of oxygen.

The evolution of great lakes management

In the late 1960s, growing public concern about the deterioration of water quality in the Great Lakes stimulated new investment in pollution research, especially the problems of eutrophication and DDT. Governments responded to the concern by controlling and regulating pollutant discharges and assisting with the construction of municipal sewage treatment works. This concern was formalized in the first Great Lakes Water Quality Agreement between Canada and the USA in 1972.

Major reductions were made in pollutant discharges in the 1970s. The results were visible. Nuisance conditions occurred less frequently as floating debris and oil slicks began to disappear. Dissolved oxygen levels improved, eliminating odor problems. Many beaches reopened as a result of improved sewage control, and algal mats disappeared as nutrient levels declined. The initiatives of the 1970s showed that improvements could be made and provided several important lessons beyond the cleanup of localized nuisance conditions.

First, the problem of algal growth in the lakes caused by accelerated eutrophication required a lake-wide approach to measure the amount of the critical nutrient, phosphorus, entering and leaving each lake from all sources and outlets. This approach of calculating a "mass balance" of the substance was then combined with other research and mathematical modeling to set target loading limits for phosphorus entering the lake (or portions of the lake). The target load is the amount of phosphorus that will not cause excessive algal growth (i.e., an amount that could safely be assimilated by the ecosystem).

Other major lessons learned about the system resulted from research on toxic substances, initially the pesticide DDT. Toxic contaminants include persistent organic

chemicals and metals. These substances enter the lakes directly from discharges of sewage and industrial effluents and indirectly from waste sites, diffuse land runoff, and atmospheric deposition. As a result of increased research, sampling, and surveillance, toxic substances have been found to be a system-wide problem.

Toxic contaminants

Toxic contaminants pose a threat not only to aquatic and wildlife species but to human health as well. Since humans are at the top of many food chains, some toxic substances biologically accumulate or are magnified as they move through the food chain. Consequently, top predators such as lake trout and fish eating birds – cormorants, ospreys, and herring gulls – can receive extremely high exposures to these contaminants. Concentrations of toxic substances can be millions of times higher in these species than in water. As a result, the potential for human exposure to these contaminants is far greater from consumption of contaminated fish and wildlife than from drinking water.

Aquatic and wildlife species have been intensively studied, and adverse effects such as cross-bills and egg-shell thinning in birds and tumors in fish are well documented. There is less certainty about the risk to human health of long-term exposure to low levels of toxic pollutants in the lakes, but there is no disagreement that the risk to human health will increase if toxic contaminants continue to accumulate in the Great Lakes ecosystem. Long-term, low-level exposures are of concern because of subtle effects that toxic contaminants may have on reproduction, the immune system, and development in children. Relationships between environmental contaminants and diseases such as cancer are also of concern.

Understanding the lakes from an ecosystem perspective

The ecosystem approach, together with an increased emphasis on toxic substances, was given formal recognition in the second Great Lakes Water Quality Agreement signed in 1978. In 1987, management aspects of the ecosystem approach were further defined in revisions to the Agreement, calling for management plans to restore 14 beneficial uses. The beneficial uses to be restored include unimpaired use of the ecosystem by all living components, including humans.

The Agreement called for Remedial Action Plans (RAPs) to be prepared for geographic Areas of Concern (AOC) where local use impairments exist. It also called for Lakewide Management Plans to be prepared for critical pollutants that affect whole lakes or large portions of them. The purpose of these management plans is to clearly identify the key steps needed to restore and protect the lakes.

To measure restoration of ecosystem recovery, the 1987 Agreement revisions added a call for ecosystem objectives and indicators to complement the chemical objectives already provided in the Agreement. These biological measures of ecosystem integrity provide an important element

of the ecosystem approach and are being developed as part of the process for developing lake-wide management plans. Ecosystem indicators have already been adopted for Lake Superior. These indicators are organisms such as bird or fish populations that tell us whether the ecosystem is healthy and whether these populations are stable and self-reproducing.

The concepts of mass balance, system-wide contamination, and bioaccumulation in the food chain have become essential components in understanding the lakes from an ecosystem perspective. For example, the mass balance approach to phosphorus control has been used to formulate target pollutant loadings for the lower lakes.

Over 33 million people who live in the Great Lakes basin and their governments face an immense challenge for the future of the basin. The wise management needed to maintain the use of Great Lakes resources requires greater public awareness, the forging of political will to protect the lakes, and creative government action and cooperation.

The Great Lakes are surrounded by two sovereign nations, a Canadian province, eight American states, and thousands of local, regional, and special-purpose governing bodies with jurisdiction for management of some aspects of the basin or the lakes. Cooperation is essential because problems such as water consumption, diversions, lake levels, and shoreline management do not respect political boundaries.

With this in mind, public consultations that include residents, private organizations, industry, and government are considered to be an essential part of the decision-making process for managing the resources of the Great Lakes ecosystem. Residents of the basin have been empowered to participate in the problem-solving process, promote healthy sustainable environments, and reduce their personal exposure to Great Lakes contaminants.

Humans are part of and depend on the natural ecosystem of the Great Lakes but may be damaging the capacity of the system to renew and sustain itself and the tile within it. Protection of the lakes for future use requires a greater understanding of how past problems developed, as well as continued remedial action to prevent further damage.

Geology

The foundation for the present Great Lakes basin was set about 3 billion years ago during the Precambrian Era. This era occupies about five-sixths of all geological time and was a period of great volcanic activity and tremendous stresses, which formed great mountain systems. Early sedimentary and volcanic rocks were folded and heated into complex structures – these were later eroded and today appear as the gently rolling hills and small mountain remnants of the Canadian Shield, which forms the northern and north-western portions of the Great Lakes basin. Granitic rocks of the shield extend southward beneath the Paleozoic sedimentary rocks where they form the “basement” structure of the southern and eastern portions of the basin.

With the coming of the Paleozoic Era, most of central North America was flooded again and again by marine seas, which were inhabited by a multitude of life forms, including corals, crinoids, brachiopods, and mollusks. The seas deposited lime silts, clays, sand, and salts, which eventually consolidated into limestone, shales, sandstone, halite, and gypsum.

During the Pleistocene Epoch, the continental glaciers repeatedly advanced over the Great Lakes region from the north. The first glacier began to advance more than a million years ago. As they inched forward, the glaciers, up to 2,000 m thick, scoured the surface of the earth, leveled the hills, and altered forever the previous ecosystem. Valleys created by the river systems of the previous era were deepened and enlarged to form the basins for the Great Lakes. Thousands of years later, the climate began to warm, melting and slowly shrinking the glacier. This was followed by an interglacial period during which vegetation and wildlife returned. The whole cycle was repeated several times.

Sand, silt, clay, and boulders deposited by the glaciers occur in various mixtures and forms. These deposits are collectively referred to as “glacial drift” and include features such as moraines, which are linear mounds of poorly scoured material or “till,” flat till plains, till drumlins, and eskers formed of well-sorted sands and gravels deposited from meltwater. Areas having substantial deposits of well-sorted sands and gravels (eskers, kames, and outwash) are usually significant groundwater storage and transmission areas or aquifers. These also serve as excellent sources of sand and gravel for commercial extraction.

As the glacier retreated, large volumes of meltwater occurred along the front of the ice. Because the land was greatly depressed at this time from the weight of the glacier, large glacial lakes formed. These lakes were much larger than the present Great Lakes. Their legacy can still be seen in the form of beach ridges, eroded bluffs, and flat plains located hundreds of meters above present lake levels. Glacial lake plains known as “lacustrine plains” occur around Saginaw Bay and west and north of Lake Erie.

As the glacier receded, the land began to rise. This uplift (at times relatively rapid) and the shifting ice fronts caused dramatic changes in the depth, size, and drainage patterns of the glacial lakes. Drainage from the lakes occurred variously through the Illinois River Valley (toward the Mississippi River), the Hudson River Valley, the Kewartha Lakes Trent River, and the Ottawa River Valley before entering their present outlet through the St. Lawrence River Valley. Although the uplift has slowed considerably, it is still occurring in the northern portion of the basin. This, along with changing long-term weather patterns, suggests that the lakes are not static and will continue to evolve.

Climate of the great lakes

The weather in the Great Lakes basin is affected by three factors: air masses from other regions, the location of the basin within a large continental landmass, and the

moderating influence of the lakes themselves. The prevailing movement of air is from the west. The characteristically changeable weather of the region is the result of alternating flows of warm air from the Gulf of Mexico and cold, dry air from the Arctic.

In summer, the northern region around Lake Superior generally receives cool, dry air masses from the Canadian northwest. In the south, tropical air masses originating in the Gulf of Mexico are most influential. As the Gulf air crosses the lakes, the bottom layers remain cool while the top layers are warmed. Occasionally, the upper layer traps the cooler air below, which in turn traps moisture and airborne pollutants and prevents them from rising and dispersing (temperature inversion). This can result in dank, humid days in areas in the midst of the basin, such as Michigan and Southern Ontario, and can also cause smog in low-lying industrial areas.

Increased summer sunshine warms the surface layer of water in the lakes, making it tighter than the colder water below. In the fall and winter months, release of the heat stored in the lakes moderates the climate near the shores of the lakes. Parts of Southern Ontario, Michigan, and western New York enjoy milder winters than similar mid-continental areas at lower latitudes.

In the autumn, the rapid movement and occasional clash of warm and cold air masses through the region produce strong winds. Air temperatures begin to drop gradually, and less sunlight, combined with increased cloudiness, signals more storms and precipitation. Late autumn storms are often the most perilous for navigation and shipping on the lakes.

In winter, the Great Lakes region is affected by two major air masses. Arctic air from the northwest is very cold and dry when it enters the basin but is warmed and picks up moisture traveling over the comparatively warmer lakes. When it reaches the land, the moisture condenses as snow, creating heavy snowfalls on the lee side of the lakes in areas frequently referred to as snowbelts. For part of the winter, the region is affected by Pacific air masses that have lost much of their moisture crossing the western mountains. Less frequently, air masses enter the basin from the southwest, bringing in moisture from the Gulf of Mexico. This air is slightly warmer and more humid. During the winter, the temperature of the lakes continues to drop. Ice frequently covers Lake Erie but seldom fully covers the other lakes.

Spring in the Great Lakes region, like autumn, is characterized by variable weather. Alternating air masses move through rapidly, resulting in frequent cloud cover and thunder storms. By early spring, the warmer air and increased sunshine begin to melt the snow and lake ice, starting again the thermal layering of the lakes. The lakes are slower to warm than the land and tend to keep adjacent land areas cool, thus prolonging cool conditions sometimes well into April. Most years, this delays the leafing and blossoming of plants, protecting tender plants, such as fruit trees, from late frosts. This extended state of dormancy allows plants from somewhat warmer climates to

survive in the western shadow of the lakes. It is also the reason for the presence of vineyards in those areas.

Climate change and the great lakes

At various times throughout its history, the Great Lakes basin has been covered by thick glaciers and tropical forests, but these changes occurred before humans occupied the basin. Present-day concern about the atmosphere is premised on the belief that society at large, through its means of production and modes of daily activity, especially by ever increasing carbon dioxide emissions, may be modifying the climate at a rate unprecedented in history.

The very prevalent greenhouse effects are actually a natural phenomenon. It is a process by which water vapor and carbon dioxide in the atmosphere absorb heat given off by the earth and radiate it back to the surface. Consequently, the earth remains warm and habitable (16°C average world temperature rather than -18°C without the greenhouse effect). However, humans have increased the carbon dioxide present in the atmosphere since the industrial revolution from 280 ppm to the present 350 ppm, and some predict that the concentration will reach twice its pre-industrial levels by the year 2500.

Climatologists, using the General Circulation Model (GCM), have been able to determine the manner in which the increase of carbon dioxide emissions will affect the climate in the Great Lakes basin. Several of these models exist and show that at twice the carbon dioxide level, the climate of the basin will be warmer by 2–4°C and slightly damper than at present. For example, Toronto's climate would resemble the present climate of southern Ohio. Warmer climates mean increased evaporation from the lake surfaces and evapotranspiration from the land surface of the basin. This in turn will augment the percentage of precipitation that is returned to the atmosphere. Studies have shown that the resulting net basin supply, the amount of water contributed by each lake basin to the overall hydrological system, will be decreased by 23–50%. The resulting decreases in average lake levels will be from half a meter to 2 m, depending on the GCM used.

Large declines in lake levels would create large-scale economic concern for the commercial users of the water system. Shipping companies and hydroelectric power companies would suffer economic repercussions, and harbors and marinas would be adversely affected. While the precision of such projections remains uncertain, the possibility of their accuracy embraces important long-term implications for the Great Lakes.

The potential effects of climate change on human health in the world's lakes are of concern not least in the Great Lakes region, and researchers can only speculate as to what might occur. For example, weather disturbances, drought, and changes in temperature and growing season could affect crops and food production in the basin. Changes in air pollution patterns as a result of climate change could affect respiratory health, causing asthma, and new disease vectors and agents could migrate into the region.

The hydrological cycle

Water is a renewable resource (Plate 2). It is continually replenished in ecosystems through the hydrological cycle. Water evaporates in contact with dry air, forming water vapor. The vapor can remain as a gas, contributing to the humidity of the atmosphere, or it can condense and form water droplets, which, if they remain in the air, form fog and clouds. In the Great Lakes basin, for example, much of the moisture in the region evaporates from the surface of the lakes. Other sources of moisture include the surface of small lakes and tributaries, moisture on the land mass, and water released by plants. Global movements of air also carry moisture into the basin, especially from the tropics.

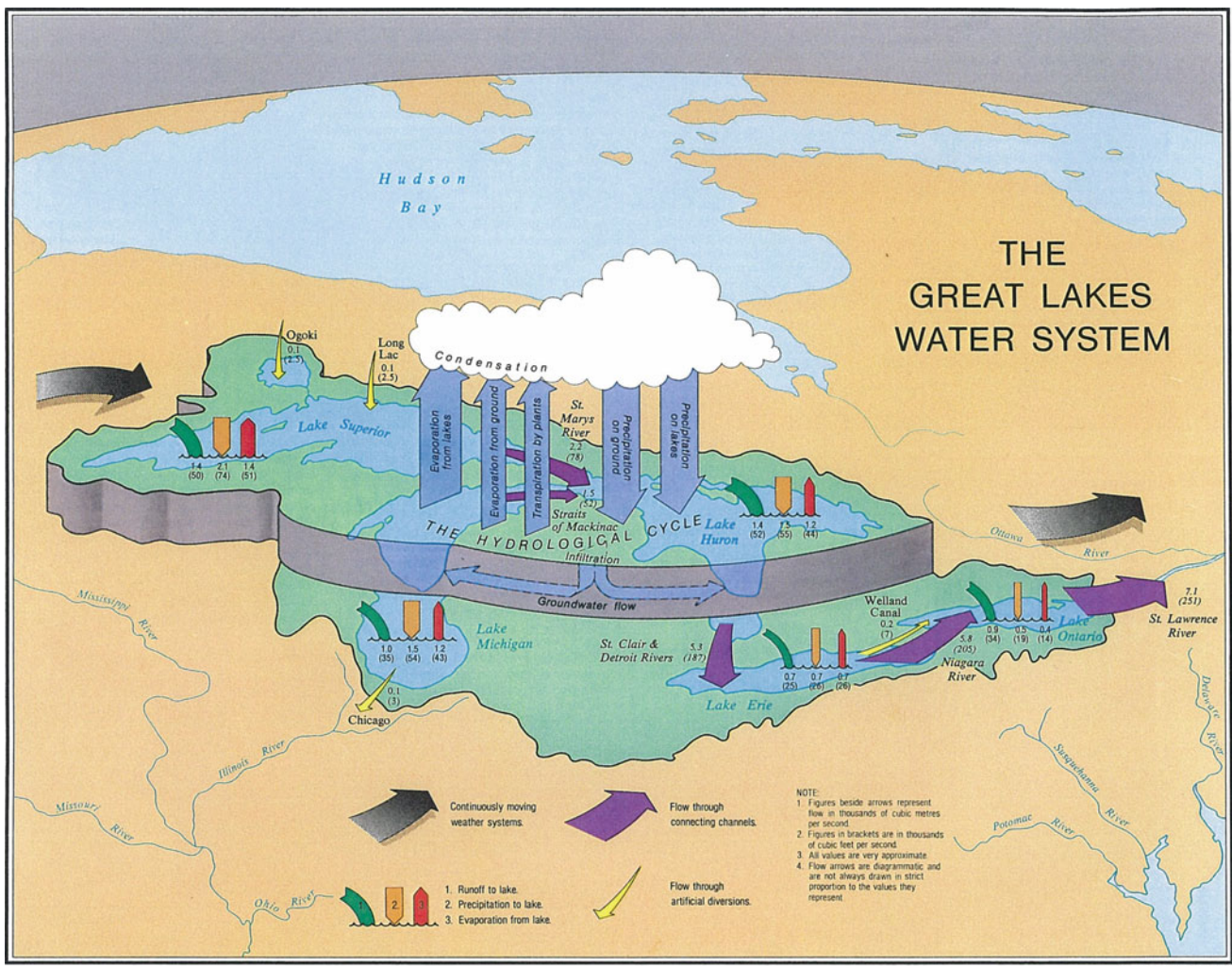
Moisture-bearing air masses move through the Great Lakes basin and deposit their moisture as rain, snow, hail, or sleet. Some of this precipitation returns to the atmosphere, and some falls on the surfaces of the Great Lakes

to become part of the vast quantity of stored fresh water once again. Precipitation that falls on the land returns to the lakes as surface runoff or infiltrates the soil and becomes groundwater.

Whether it becomes surface runoff or groundwater depends upon a number of factors. Sandy soils, gravels, and some rock types in the basin contribute to groundwater flows, whereas clays and impermeable rocks contribute to surface runoff. Water falling on sloped areas tends to run off rapidly, while water falling on flat areas tends to be absorbed or stored on the surface. Vegetation also tends to decrease surface runoff; root systems hold moisture-laden soil readily, and water remains on plants.

Surface runoff

Surface runoff is a major factor in the character of the Great Lakes basin. Rain falling on exposed soil tilled for agriculture or cleared for construction accelerates erosion



Great Lakes, North America, Plate 2 The Great Lakes Water System.

and the transport of soil particles and pollutants into tributaries. Suspended soil particles in water are deposited as sediment in the lakes and often collect near the mouths of tributaries and connecting channels. Much of the sediment deposited in nearshore areas is resuspended and carried farther into the lake during storms. The finest particles, clays and silts, may remain in suspension long enough to reach the mid-lake areas.

Before settlement of the basin, streams typically ran clear year-round because natural vegetation prevented soil loss. Clearing of the original forest for agriculture and logging has resulted in both more erosion and runoff into the streams and lakes. This accelerated runoff aggravates flooding problems.

Groundwater

Groundwater is important to the Great Lakes ecosystem because it provides a reservoir for storing water and slowly replenishing the lakes in the form of base flow in the tributaries. It is also a source of drinking water for many communities in the Great Lakes basin. Shallow groundwater also provides moisture to plants.

As water passes through subsurface areas, some substances are filtered out, but some materials in the soils become dissolved or suspended in the water. Salts and minerals in the soil and bedrock are the source of what is referred to as "hard" water, a common feature of well water in the lower Great Lakes basin.

Groundwater can also pick up materials of human origin that have been buried in dumps and landfill sites. Groundwater contamination problems can occur in both urban-industrial and agricultural areas. Protection and inspection of groundwater is essential to protect the quality of the entire water supply consumed by basin populations because the underground movement of water is believed to be a major pathway for the transport of pollution to the Great Lakes. Groundwater may discharge directly to the lakes or indirectly as base flow to the tributaries.

Lake levels

The Great Lakes are part of the global hydrological system. Prevailing westerly winds continuously carry moisture into the basin in air masses from other parts of the continent. At the same time, the basin loses moisture in departing air masses by evaporation and transpiration and through the outflow of the St. Lawrence River. Over time, the quantity lost equals what is gained, but lake levels can vary substantially over short-term, seasonal, and long-term periods.

Day-to-day changes are caused by winds that push water on shore (wind set-up). This is usually associated with a major lake storm, which may last for hours or days. Another extreme form of oscillation (seiche) occurs with rapid changes in winds and barometric pressure.

Annual or seasonal variations in water levels are based mainly on changes in precipitation and runoff to the Great Lakes. Generally, the lowest levels occur in winter when

much of the precipitation is locked up in ice and snow on land and dry winter air masses pass over the lakes, enhancing evaporation. Levels are highest in summer after the spring thaw when runoff increases.

The irregular long-term cycles correspond to long-term trends in precipitation and temperature, the causes of which have yet to be adequately explained. Highest levels occur during periods of abundant precipitation and lower temperatures that decrease evaporation. During periods of high lake levels, storms cause considerable flooding and shoreline erosion, which often result in property damage. Much of the damage is attributable to intensive shore development, which alters protective dunes and wetlands, removes stabilizing vegetation, and generally reduces the ability of the shoreline to withstand the damaging effects of wind and waves.

The International Joint Commission, the binational agency established under the Boundary Waters Treaty of 1909 between Canada and the USA, has the responsibility for regulation of flows on the St. Marys and the St. Lawrence Rivers. These channels have been altered by enlargement and placement of control works associated with deep-draft shipping. Agreements between the USA and Canada govern the flow through the control works in these connecting channels.

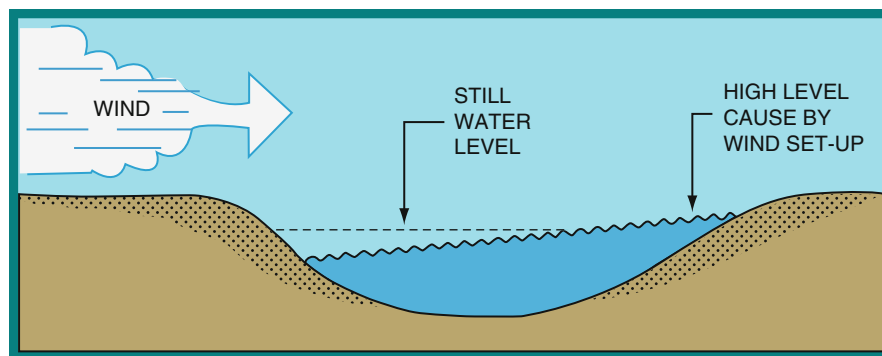
The water from Lake Michigan flows to Lake Huron through the Straits of Mackinac. These straits are deep and wide, resulting in Lakes Michigan and Huron standing at the same elevation. There are no artificial controls on the St. Clair and Detroit Rivers that could change the flow from the Michigan-Huron Lakes system into Lake Erie. The outflow of Lake Erie via the Niagara River is also uncontrolled, except for some diversion of water through the Welland Canal. A large percentage of the Niagara River flow is diverted through hydroelectric power plants at Niagara Falls, but this diversion has no effect on lake levels.

Studies of possible further regulation of flows and lake levels have concluded that natural fluctuation is huge compared with the influence of existing control works. Further regulation by engineering systems could not be justified in light of the cost and other impacts. Just two and a half centimeters of water on the surface of Lakes Michigan and Huron amounts to more than 36 billion cubic meters of water (about 1,260 billion cubic feet) (Figure 1).

Lake processes: stratification and turnover

The Great Lakes are not simply large containers of uniformly mixed water. They are, in fact, highly dynamic systems with complex processes and a variety of subsystems that change seasonally and on longer cycles.

The stratification or layering of water in the lakes is due to density changes caused by changes in temperature. The density of water increases as temperature decreases until it reaches its maximum density at about 4° Celsius. This causes thermal stratification or the tendency of deep lakes to form distinct layers in the summer months. Deep water



Great Lakes, North America, Figure 1 Wind set-up is a local rise in water caused by winds pushing water to one side of a lake.

is insulated from the sun and stays cool and more dense, forming a lower layer (the hypolimnion). Surface and nearshore waters are warmed by the sun, making them less dense so that they form a surface layer – the epilimnion. As the summer progresses, temperature differences increase between the layers. A thin middle layer, or thermocline, develops in which a rapid transition in temperature occurs.

The warm epilimnion supports most of the life in the lake. Algal production is greatest near the surface where the sun readily penetrates. The surface layer is also rich in oxygen, which is mixed into the water from the atmosphere. A second zone of high productivity exists just above the hypolimnion due to upward diffusion of nutrients. The hypolimnion is less productive because it receives less sunlight. In some areas, such as the central basin of Lake Erie, it may lack oxygen because of decomposition of organic matter.

In late fall, surface waters cool, become denser, and descend, displacing deep waters and causing a mixing or turnover of the entire lake. In winter, the temperature of the lower parts of the lake approaches 4°C (39°F) while surface waters are cooled to the freezing point and ice can form. As temperatures and densities of deep and shallow waters change with the warming of spring, another turnover may occur. However, in most cases, the lakes remain mixed throughout the winter.

The layering and turnover of water annually are important for water quality. Turnover is the main way in which oxygen-poor water in the deeper areas of the lakes can be mixed with surface water containing more dissolved oxygen. This prevents “anoxia”, or complete oxygen depletion, of the lower levels of most of the lakes. However, the process of stratification during the summer also tends to restrict dilution of pollutants from effluents and land runoff.

During the spring warming period, the rapidly warming nearshore waters are inhibited from moving to the open lake by a thermal bar, a sharp temperature gradient that prevents mixing until the sun warms the open lake surface waters or until the waters are mixed by

storms. Because the thermal bar holds pollutants nearshore, they are not dispersed to the open waters and can become more concentrated within the nearshore areas (Figure 2).

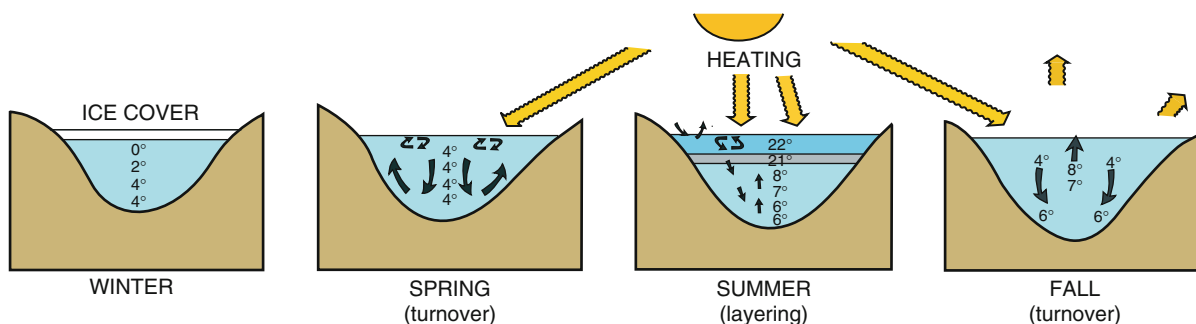
Living resources

As an ecosystem, the Great Lakes basin is a unit of nature in which living organisms and nonliving things interact adaptively. An ecosystem is fuelled by the sun, which provides energy in the form of light and heat. This energy warms the earth, the water, and the air, causing wind current evaporation and precipitation. The light energy of the sun is essential for the photosynthesis of green plants in water and on land. Plants grow when essential nutrients such as phosphorus and nitrogen are present with oxygen, inorganic carbon, and adequate water.

Plant material is consumed in the water by zooplankton, which graze the waters for algae, and on land by plant-eating animals (herbivores). Next in the chain of energy transfer through the ecosystem are organisms that feed on other animals (carnivores) and those that feed on both animals and plants (omnivores); together these levels of consumption constitute the food chain or web, a system of energy transfers through which an ecological community consisting of a complex of species is sustained. The population of each species is determined by a system of checks and balances based on factors such as the availability of food and the presence of predators, including disease organisms.

Every ecosystem also includes numerous processes to break down accumulated biomass plants, animals, and their wastes into the constituent materials and nutrients from which they originated. Decomposition involves microorganisms that are essential to the ecosystem because they recycle matter that can be used again.

Stable ecosystems are sustained by the interactions that cycle nutrients and energy in a balance between available resources and the life that depends on those resources. In ecosystems, including the Great Lakes basin, everything depends on everything else and nothing is ever really wasted.



Great Lakes, North America, Figure 2 Lake stratification (layering) and turnover. Heat from the sun and changing seasons cause water in large lakes to stratify or form layers. In winter, the ice cover stays at 0° C (32° F) and the water remains warmer below the ice than in the air above. Water is most dense at 4° C (39° F). In the spring turnover, warmer water rises as the surface heats up. In fall, surface waters cool, become denser, and descend as heat is lost from the surface. In summer, stratification is caused by a warming of surface waters, which form a distinct layer called the epilimnion. This is separated from the cooler and denser waters of the hypolimnion by the thermocline, a layer of rapid temperature transition. Turnover distributes oxygen annually throughout most of the lakes.

The ecosystem of the Great Lakes and the life supported within it have continuously altered with time. Through periods of climate change and glaciation, species moved in and out of the region; some perished and others pioneered under changed circumstances. None of the changes, however, has been as rapid as that which occurred with the arrival of European settlers.

When the first Europeans arrived in the basin nearly 400 years ago, it was a lush, thickly vegetated area. Vast timber stands consisting of oaks, maples, and other hardwoods dominated the southern areas. Only a very few small vestiges of the original forest remain today. Between the wooded areas were rich grasslands with growth as high as 2 or 3 m. In the north, coniferous forests occupied the shallow, sandy soils interspersed by bogs and other wetlands.

The forest and grasslands supported a wide variety of life, such as moose in the wetlands and coniferous woods, and deer in the grasslands and brush forests of the south. The many waterways and wetlands were home to beaver and muskrat which, with the fox, wolf, and other fur-bearing species, inhabited the mature forest lands. These were trapped and traded as commodities by the native people and the Europeans. Abundant bird populations thrived on the various terrains, some migrating to the south in winter, others making permanent homes in the basin.

It is estimated that there were as many as 180 species of fish indigenous to the Great Lakes. Those inhabiting the nearshore areas included smallmouth and largemouth bass, muskellunge, northern pike, and channel catfish. In the open water were lake herring, blue pike, lake whitefish, walleye, sauger, freshwater drum, lake trout, and white bass. Because of the differences in the characteristics of the lakes, the species composition varied for each of the Great Lakes. Warm, shallow Lake Erie was the most productive, while deep Superior was the least productive.

Changes in the species composition of the Great Lakes basin in the last 200 years have been the result of human activities. Many native fish species have been lost by overfishing, habitat destruction, or the arrival of exotic or non-indigenous species, such as the lamprey and the alewife. Pollution, especially in the form of nutrient loading and toxic contaminants, has placed additional stresses on fish populations. Other human-made stresses have altered reproductive conditions and habitats, causing some varieties to migrate or perish. Still other effects on lake life result from damming, canal building, and altering or polluting tributaries to the lakes in which spawning takes place and where distinct ecosystems once thrived and contributed to the larger basin ecosystem.

Recreation

Since early in the industrial age, the waterways, shorelines, and woodlands of the Great Lakes region have been attractions for leisure time activities. Many of the utilitarian activities that were so important in the early settlement and industrial development became recreational activities in later years. For example, boating, fishing, and canoeing were once commercial activities, but are now primarily leisure pursuits.

Recreation in the area became an important economic and social activity with the age of travel in the nineteenth century. A thriving pleasure boat industry based on the newly constructed canals developed, bringing people into the region in conjunction with rail and road travel. Niagara Falls attracted travelers from considerable distances and was one of the first stimulants to the growth of a leisure-related economy. Later, the reputation of the lower lakes region as the frontier of a pristine wilderness drew people seeking restful cures and miracle waters to the many spas and "clinics" that developed along the waterway.

In the twentieth century, more people had more free time. With industrial growth, greater personal disposable income, and shorter work weeks, people of all walks of life began to spend their leisure time beyond the city limits. Governments on both sides of the border acquired lands and began to develop an extensive system of parks, wilderness areas, and conservation areas in order to protect valuable local resources and to serve the needs of the population for recreation areas. Unfortunately, by the time the need for publicly accessible recreation lands had become apparent, much of the land in the basin, including virtually all the shoreline on the lower lakes, was in private hands. Today, about 80% of the US shoreline and 20% of the Canadian shore is privately owned and not accessible by the public.

The recreation industry includes production and sale of sports equipment and boats, marinas, resorts, restaurants, and related service industries that cater to a wide range of recreational activities. In some areas of the basin, recreation and tourism are becoming an increasingly important component of the economy in place of man manufacturing. The Great Lakes basin provides a wide range of recreational opportunities, ranging from pristine wilderness activities in national parks such as Isle Royale and Pukaskwa to intensive urban waterfront beaches in major urban areas.

The increasingly intensive recreational development of the Great Lakes has had mixed impacts. Some recreational activities cause environmental damage. Extensive development of cottage areas, summer home sites, beaches, and marinas has resulted in loss of wetland, dune, and forest areas. Shoreline alteration by developers and individual property owners has caused changes in the shoreline erosion and deposition process, often to the detriment of important beach and wetland systems that depend upon these processes. The development of areas susceptible to flooding and erosion has caused considerable public reaction. There is pressure to manage lake levels to prevent changes that are part of natural weather patterns and processes. Pollution from recreational sites and boats has also caused water-quality degradation.

Recreational uses are a threat to the quality of the Great Lakes ecosystem, but also provide a basis for protecting quality by attracting and involving people who recognize that protection of the ecosystem is essential to sustain the recreation that they value. People who use the water for its fun and beauty can become a potent force in the protection of the ecosystem. Naturalists, anglers, and cottagers were among the first to bring environmental issues to the attention of the public and call for the cleanup of the lakes in the 1950s and 1960s when eutrophication threatened favored fishing, bathing, and wildlife sites. Today, more people than ever use and value the lakes for recreational purposes.

Recent years have seen a major resurgence in recreational fishing as the walleye fisheries recover and the

new salmon fisheries develop. Lake Ontario now sports a very important salmon and trout recreational fishery. The water-quality recovery in Lake Erie has been complemented by record walleye reproduction in recent years. In many areas – Buffalo, Cleveland, Chicago, and Toronto particularly – there have been urban renewal movements with the lake front as a primary focus. Developing public access to the water is a key element of these renewal projects.

Nutrients

Temperatures of many tributaries have been increased by removal of vegetative shade cover and some by thermal pollution. But, more importantly, the amount of nutrients and organic material entering the lakes has increased with intensified urbanization and agriculture. Nutrient loading increased with the advent of phosphate detergents and inorganic fertilizers. Although controlled in most jurisdictions bordering the Great Lakes, phosphates in detergents continue to be a problem where they are not regulated.

Increased nutrients in the lakes stimulate the growth of green plants, including algae. The amount of plant growth increases rapidly in the same way that applying lawn fertilizers – nitrogen, phosphorus, and potassium – results in rapid, green growth. In the aquatic system, the increased plant life eventually dies, settles to the bottom, and decomposes. During decomposition, the organisms that break down the plants use up oxygen dissolved in the water, near the bottom. With more growth, there is more material to be decomposed and more consumption of oxygen. Under normal conditions, when nutrient loadings are low, dissolved oxygen levels are maintained by the diffusion of oxygen into water, mixing by currents and wave action, and by the oxygen production of photosynthesizing plants.

The Boundary Waters Treaty of 1909

In 1905, the International Waterways Commission was created to advise the governments of both countries about levels and flows in the Great Lakes, especially in relation to the generation of electricity by hydropower.

Its limited advisory powers proved inadequate for problems related to pollution and environmental damage. One of its first recommendations was for a stronger institution with the authority for study of broader boundary water issues and the power to make binding decisions.

The Boundary Waters Treaty was signed in 1909 and provided for the creation of the International Joint Commission (IJC). The IJC has the authority to resolve disputes over the use of water resources that cross the international boundary. Most of its efforts for the Great Lakes have been devoted to carrying out studies requested by the governments and advising the governments about problems.

In 1912, water pollution was one of the first problems referred to the IJC for study. In 1919, after several years

of study, the IJC concluded that serious water quality problems required a new treaty to control pollution. However, no agreement was reached.

Additional studies in the 1940s led to new concerns by the IJC. The Commission recommended that water quality objectives be established for the Great Lakes and that technical advisory boards be created to provide continuous monitoring and surveillance of water quality.

Public and scientific concern about pollution of the lakes grew as accelerated eutrophication became more obvious through the 1950s. In 1984, the IJC began a new reference study on pollution in the lower Great Lakes. The report on this study in 1970 placed the principal blame for eutrophication on excessive phosphorus.

The study proposed basin-wide efforts to reduce phosphorus loadings from all sources. It was recognized that reduction of phosphorus depended on control of local sources. Uniform effluent limits were urged for all industries and municipal sewage treatment systems in the basin. Research suggested that land runoff could also be an important source of nutrients and other pollutants into the lakes. The result of the reference study was the signing of the first Great Lakes Water Quality Agreement in 1972.

Acknowledgment

Acknowledgement is made to Environment Canada for permission to reproduce extracts and figures from *The Great Lakes, An Environmental Atlas and Resource Book*, Third Edition 1995, and to the Government of Canada and the United States Environmental Protection Agency.

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[Thermal Regime of Lakes](#)
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GREAT SALT LAKE

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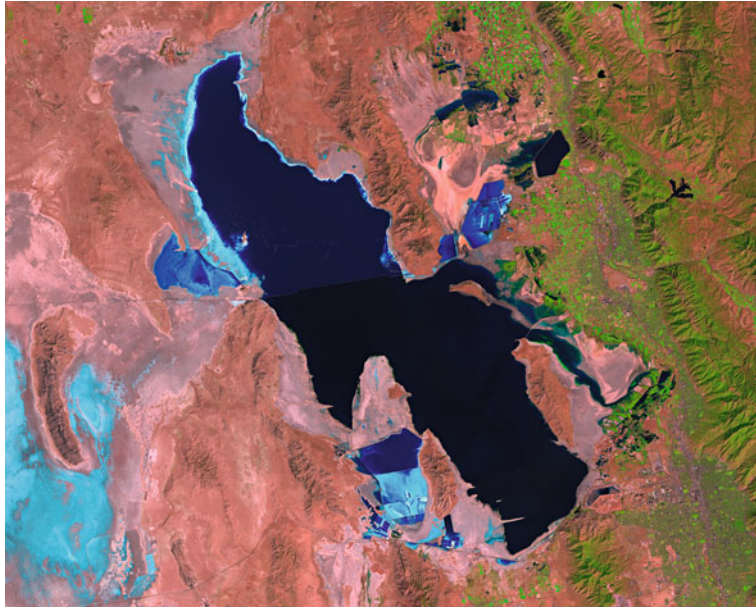
Description

The origin of the Great Salt Lake in the USA can be traced back to ancient Lake Bonneville which covered much of western Utah and small parts of Idaho and Nevada during the Pleistocene Epoch (known as the Great Ice Age) between 23,000 and 12,000 years ago in the warmer and drier period that followed the Ice Age. Lake Bonneville receded and the Great Salt Lake as it is today is a descendant of that ancient lake (Fig. 1).

The combination of size and salt content makes the Great Salt Lake unique. Since the lake has no outlet, all the minerals brought in from the nearby mountains remain in the lake. It is estimated that more than two million tons of minerals are added to the lake each year and the lake has a dissolved mineral content of some four to five billion tons, although these figures vary as the salinity of the lake varies. The lake is one of the saltiest bodies of water in the world, and only the Dead Sea between Israel and Jordan has a higher salt content. The percentage of salt in the lake varies depending on the water level, and percentages of salt as great as 27% have been found in the lake. The lake level has been monitored since 1847. The inflow to the lake is mainly from the streams Bear, Weber, and Jordan; precipitation; and groundwater. The lake loses water by evaporation from the surface. So long as inflow exceeds evaporation, the lake level will rise, and because the lake is mainly closed, a small change in depth results in a large change in surface area, and, therefore, the position of the shoreline is extremely variable. A prolonged period of wet weather in 1982–1986 caused the lake to flood parts of Salt Lake City and threatened the transcontinental railroad and highways along the shores.

There are eight named islands in the lake that have never been totally submerged. All have been connected to the mainland by exposed shoals during periods of low water. They range in size from Antelope Island with an area of 93 million squaremeters to Hat Island with an area of 90,000 m².

The Great Salt Lake was only discovered in the winter of 1824–1825 by Jim Bridger, but the first exploration was conducted by John C. Freeman and his party in 1843. The railroad was commenced across the lake in 1902 when a 12-mile-long trestle of 28,000 wooden pilings crossed Great Salt Lake and made the railroad an integral part of the lake. After World War II, a causeway was built to replace the trestle across the lake.



Great Salt Lake, Figure 1 Landsat 5 image of Great Salt Lake, September 2010 (Courtesy of the USGS).

The Great Salt Lake has a variable surface area of 5,950 km² and an average capacity of 1.6 million. The altitude of the lake is 1,250 m above mean sea level and is about 110 km long and about 50 km wide at the elevation of 1,250 m. The depth of the lake varies with surface area but has an average of about 4 m.

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H

HAZARDS

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General concepts

The concept of hazard identification and management is widely acknowledged in many fields, including environmental and health and safety management, as a tool for preventing or minimizing harm. A hazard may be defined as a situation with the potential to cause harm. Three main elements are contained within the hazard definition: *situation*, *harm*, and *potential*. Situation refers to what could occur (e.g., heavy metals may enter surface waters). Harm may be in terms of detriment, injury, or ill health to people; damage to the environment; or a combination of these, for example, contamination of lake sediments. However, it is not sufficient to identify only what could occur if hazards are to be managed. The possible likelihood and extent of the potential effects need to be determined in order that action can be taken.

This introduces the concept of risk and the assessment and management of risk. The risk from a hazardous situation is a combination of the likelihood that it will cause harm and the magnitude of the harm that could be caused. The risk concept therefore moves from a pure identification of what harm could occur to a determination of what harm is likely to occur and what may cause the most harm (i.e., the likelihood and consequences of a hazardous event occurring (BSI, 2007)). Once determined, risks can then be assessed to decide whether they are acceptable. Risk assessment informs decisions on how to manage risks and is therefore the overall process of determining the likelihood and consequences of a hazardous situation occurring, estimating

the level of the risk, and deciding upon how to manage the risk based on the measures taken and which could be taken (BSI, 2007). The link between hazard and risk must be understood if hazardous situations and hence risks are to be managed.

There is a plethora of techniques for risk assessment ranging from simple risk screening (e.g., where the risk is undeniably negligible) to complex methods of assigning data to risks. Two main methods of risk assessment exist: quantitative and qualitative. Quantitative risk assessment is an objective approach to the assessment of risk. Quantitative risk assessment techniques are generally mathematics/engineering based, complex, and aim to quantify risk expressed in units such as incidents of a certain severity per annum (Guy, 2001). Conversely, qualitative risk assessment is a subjective approach to risk assessment that considers that the perception of risk is different to different people depending on their experiences (Guy, 2001). Qualitative risk assessment may encompass a simple semiquantification of risk such as assigning defined categorizations of low, medium, and high as both measures of the severity of consequences and the likelihood of occurrence. However, these labels are generally assigned based on the perception of the assessors rather than specific calculation. Despite their inherent differences, generally, risk assessments follow the same underlying process (BSI, 2007; Pollard and Guy, 2001):

1. Identification of hazards
2. Determination of the risks associated with the hazards by:
 - (a) Identification of the potential consequences of the hazard
 - (b) Determining the potential severity of harm
 - (c) Assigning a value or judgment (be it quantitative or qualitative) to the likelihood of the potential hazard being realized

3. Preparation of a relative hierarchy of risks by relating them to other risks
4. Deciding if the risks are acceptable by reference to standard approaches to measuring tolerability and/or taking into account economic, social, technological, or management issues
5. Preparation and implementation of a risk control plan as necessary based on the prepared hierarchy and acceptability of the risks
6. Reviewing and monitoring the risk assessment process and risk control plan as necessary

Risk management is the holistic process of hazard identification, risk assessment, and risk control, with the greatest risks (be they determined objectively or subjectively) being the priority with regard to action to manage those risks. Therefore, there is an obvious need for consideration of both quantitative and qualitative risk assessment in order to manage hazards and risks particularly where public perception is inherent to the methods adopted for risk management (Guy, 2001). However, it is essential to consider that while risk assessment can provide useful information, it cannot, by its nature, fully take account of the uncertainties of people. Risk management strategies for lakes and reservoirs may require that hazards and risks are assessed and considered in terms of the entire body of water and its environment and that there is coordination between those placing demands of the water (UNEP, 1994). In addition, the management of lakes and reservoirs may need to encompass the concept of sustainability by meeting the needs of the present without compromising the future.

Hazards associated with lakes and reservoirs

Lakes and reservoirs are associated with hazards. The hazards may be *to* (e.g., pollution or silting) or *from* (e.g., working on or near water) the lake or reservoir. Hazards related to lakes and reservoirs include: water quality; pollution; silting; pathogens; drought; land use; flooding; habitat destruction; security; public access; working over, on, or near water; habitat destruction; and reservoir safety hazards.

Water quality

The quality of freshwater is vitally important for many ecosystems. Not only is water used to fulfill the basic human needs of drinking, cooking, and washing but for a plethora of other domestic, commercial, agricultural, industrial, and recreational activities. In addition, water provides a biologically diverse habitat for wildlife. Despite the demands placed upon it, the water found in rivers and freshwater lakes accounts for around a quarter of one percent of all the freshwater on the planet (UNEP, 1994). Therefore, water quality and its management is a balance between the different uses of water. Water quality hazards arise when water quality is adversely affected, commonly by human activity causing pollution in some form or another. The management of

water quality to minimize risk needs to incorporate measures to prevent and mitigate hazards through technological, managerial, social, and legislative actions.

Pollution

Pollution may be variously defined; however, it is generally the entry of substances or energies into the environment that are potentially harmful to ecological systems, (NSCA, 1992). It is inextricably linked to water quality and is arguably its greatest threat with many human activities either polluting or having the potential to pollute water (including recreational activities). Pollution may be caused directly or indirectly, accidentally or deliberately, slowly or quickly and can arise from a point source, such as commercial or industrial discharges, or may be more dispersed and diffuse, such as agricultural runoff or urban drainage (Environment Agency, 2004). However, whatever its method of delivery, pollution can have wide ranging effects in the short, medium, and long term. Pollution from point sources is relatively simple to control by technological, managerial, and legal processes. However, because of the nature of diffuse pollution that arises from hundreds or thousands of sources, it is more difficult to control (CIWEM, 2003). Pollution may enter lakes and reservoirs by direct entry to surface water, entry to groundwater, runoff from the land, or deposition from the atmosphere.

A general list of pollutants entering the water cycle includes: chemicals (organic and inorganic), radioactivity, heat, oxygen-consuming matter, inert solids, wastes (solid and liquid), sewage, nutrients, and microorganisms. All these pollutants have potentially adverse effects on water quality depending upon their exact nature in terms of chemical, biological, and physical properties; quantity; and concentration. The consequences of pollution include: toxic effects on flora and fauna, eutrophication, silting, increase in pathogens, increased water treatment costs, adverse visual effects, and loss of habitat.

Silting

Silting refers to the deposition of sediments. Its causes are varied and include soil erosion and a decrease in the velocity of water in a lake or reservoir. The sediment carried into a body of water may contain nutrients or contaminants that have adverse effects on water quality. In addition, silting may lead to decreased water storage capacity and loss of wildlife habitat. Measures to reduce silting include the proactive minimization of ground and surface erosion, particularly in catchment areas, and reduction of pollution and reactive dredging of silted areas.

Pathogens

Pathogens are disease-causing organisms and include bacteria, viruses, and parasitic worms (helminth). Pathogens may enter surface water via contaminated biological wastes, including human and animal fecal wastes, and emanate from both distinct and diffuse sources. Large

numbers of pathogens may be found in lakes particularly after rainfall when surface runoff carries contaminated material from the land into the water (Severn Trent Water, 2004). Diseases caused by pathogens are wide ranging and include infectious and parasitic diseases, which vary worldwide and include typhoid, cholera, and bilharzia in areas of less-developed water treatment. Risk controls for pathogens include prevention of water pollution by fecal matter by suitable wastewater treatment and effective drinking water treatment.

Drought

Drought and flooding are arguably opposites with both arising from relatively extreme fluctuations in water level due to natural or human causes. When the water level in a lake decreases either by overabstraction, lack of rainfall, or diversion of tributary rivers, this results in a decrease in lake area and volume. The potential effects of this include: temporary eutrophication, concentration of minerals in the water, damage to industries that depend on lake resources (such as for fishing or dispersion of pollution), and damage of ecosystems (UNEP, 1994). While there is no method to prevent periods of low rainfall, overabstraction may be minimized to reduce risks and other measures adopted to lessen the impact of drought such as prevention of silting and pollution and maintenance of habitats.

Flooding

The area and volume of lakes and reservoirs may increase with heavy precipitation and surface runoff, whether it is caused by predictable wet periods or thaw, or less-encountered events such as atypical rainfall. Increases to the flow into the lake or reservoir may cause flooding to the body of water itself and flooding both up- and downstream of the lake or reservoir as it reaches its natural or designed capacity. The effects of flooding include habitat damage, increased risk to the safety of people, and the damage of property. However, it must always be borne in mind that flooding in the case of natural lakes may be a normal process that brings benefits such as the conditioning and fertilization of arable land.

Risk control with regard to flooding (and drought) is concerned with the management of the effects of the environment on ecosystems and people rather than the effects of people on the environment and ecosystems (as is often the case). Risk controls for the management of flooding include: precipitation prediction; flood modeling; the development of appropriate warning and informing and emergency arrangements; the development of physical flood prevention or minimization measures such as control structures, protective walls, and water storage areas, making premises resistant to flooding; and the development of recovery arrangements.

Land use

The expansion of natural lakes and the creation or expansion of reservoirs inevitably uses land. In the case of the

latter, the perceived benefits of the land use may vary greatly. Large bodies of water cannot only create habitats for wildlife and amenities for people but also damage existing features of the natural or human landscape. Measures can be taken to minimize the expansion of natural lakes if they are likely to impinge upon habitats or resources and include increasing the outflow from the lake. The effects of the development of existing or proposed reservoirs can be minimized by environmental impact assessment, which aims to provide a balanced assessment of the need for a development that describes the proposals, provides the information used to evaluate the environmental effects, and gives details of the environmental effects and the measures taken to reduce or avoid them.

Security

People may wish to access lakes and reservoirs for leisure activities; however, they may also wish to gain access (including access to associated infrastructures) for nefarious activities. Risks associated with nefarious activities include pollution of the water, poaching, and access to buildings and infrastructure controls. General security measures that can be adopted to minimize risks include: use of closed-circuit-television (CCTV) systems and security fences; locking of access gates, doors, and inspection and access covers; adoption of security patrols and intruder detection systems; and covering of small reservoirs in populated areas.

Public access

Open water is integral to the leisure activities of many people. The main hazard associated with public access to lakes and reservoirs is drowning following accidental or deliberate entry into the water (Water UK, 1999). In the United Kingdom during 2001, drowning in lakes and reservoirs accounted for 12% of total drowning (RoSPA, 2003). Leisure activities associated with lakes and reservoirs include: walking, swimming, diving, water sports, motorized water sports, angling, and (weather conditions allowing) ice-skating. In addition to the effects on people, these activities may have effects on local flora and fauna, water quality, and the existence of pollutants such as oil and general waste. Some of these activities need to be segregated or prohibited to prevent damage to the environment and accidents to people (e.g., diving and other water sport activities should be segregated due to the risk of injury, diving may not be acceptable in sensitive nature conservation areas, pollution from motorboats may damage local ecosystems). Public safety in periods of extremes of weather (hot weather leading to bathing or easy access to infrastructure in periods of drought and cold weather leading to ice formation) is a particular consideration.

The risks associated with public access to lakes and reservoirs may be reduced by measures including: removal of reservoirs (particularly reservoirs in populated

areas); general security measures; barriers (particularly at high-risk areas); warning notices; prohibition of water activities, including water sports; provision of appropriate access routes and emergency equipment; fencing; inspection and maintenance of control measures; and the provision of information, instruction, and training to higher-risk groups (such as children) (Water UK, 1999). In addition, ice breaking may be carried out around the edges of frozen water to dissuade people from walking on it; however, this poses a risk to those undertaking the ice breaking (RoSPA, 2003).

Working over, on, or near water

Working over, on, or near water presents a danger that people may slip, trip, or fall into water or be swept off their feet by water leading to injuries and the risk of drowning. As with all work activities, working over, on, or near water needs to be carried out in a safe and healthy manner adopting appropriate control measures to minimize risks and mitigate the effects of any incident. General controls that may need to be adopted when work is carried out over, on, or near water include provision of appropriate platforms and gangways; safety nets and safety harnesses; illumination; first aid equipment; personal protective equipment and clothing, including personal buoyancy equipment; suitable means of access to and egress from the location; and suitable rescue equipment and procedures. In addition, it may be necessary to ensure work sites are suitably tidy and carefully consider the current and anticipated weather conditions (Construction Health and Safety, 2002).

Habitat destruction

Many of the hazards described thus far can have a detrimental effect on habitats. Lakes and reservoirs are a large and diverse habitat for flora and fauna. Pollution; silting; pathogens; drought; land use; flooding; security; public access; and working over, on, or near water can act to disrupt or even devastate habitats. Therefore, habitat destruction may arguably be a side effect of another hazard or combination of hazards.

Reservoir safety hazards

In addition to the hazards outlined above, reservoirs may present further hazards. Hazards associated with reservoirs are primarily associated with the structural integrity of the dam and associated infrastructure due to leakage, soil movement/slippage, water seepage, spoiling of pointing between stone blocks, and increased or unusual vegetation growth associated with the dam or embankment. Additional hazards include blockage of spillways, silting of overflows, inoperable sluice controls, burrows into soil embankments, and intrusion of vegetation into structures. With regard to occupational hazards other than those previously discussed, issues to consider include working at height and working with electricity generation and distribution infrastructures.

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Cross-references

[Acidification in Lakes](#)
[Cyanobacteria \(Blue-Green Algae\)](#)
[Dam Failures: Impact on Reservoir Safety Legislation in Great Britain](#)
[Dams, Classification](#)
[Ice Covered Lakes](#)
[Lake Sediments](#)
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HEALTH ASPECTS OF LAKES AND RESERVOIRS

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Definition

Health aspects of Lakes and Reservoirs can refer to all the ways in which the creation, existence, and use of reservoirs and other lakes can influence human health. This entry deals with the relation of lakes and reservoirs to communicable diseases chiefly, as chemical and physical hazards are largely separate while very indirect effects through changes in income or agricultural innovations

made possible by irrigation would spread the material too thinly, although they do have substantial effects.

A *reservoir* is a man-made water impoundment where the water is used in a controlled way for specific human ends. Most reservoirs are created by placing a *dam* across a stream. In some countries, and especially for small impoundments, the term *dam* is applied to the reservoir as well as the retaining wall. In South Asia the term *tank* is also used.

By *communicable diseases* we mean *infectious diseases*, which can spread directly, or through water, from the patient to other people, plus *transmissible diseases* that have an insect vector or a water snail intermediate host between the stages in the human host.

Introduction

Lakes and reservoirs have a great influence on human health, both directly and indirectly, often for the good, but also frequently leading to illness and sometimes death. Communicable, noncommunicable, and traumatic harm may all be related to lakes, whether natural or man-made. The latter are of particular importance, since by varying the way in which reservoirs are made and operated it is possible to prevent or at any rate diminish many adverse effects on health.

The unhealthy effects of reservoirs are often primarily due to the uses to which the stored water is put. In particular, the use of water for irrigated agriculture is associated with infectious and parasitic diseases, especially in the tropics. In an irrigation scheme, large populations of workers are closely and repeatedly exposed to water contact. Diseases which occurred at the margin of reservoirs and lakes may be widespread across the whole of an irrigation scheme.

The majority of all the health hazards related to communicable disease around reservoirs and lakes are due to events taking place near the edge of the lake or in shallow areas. Reservoirs in general differ from most lakes in that they have a larger annual fluctuation of depth as the water level rises and falls under human control and in relation to various needs. Usually, the consequence is that the flow of water below the dam is more evenly distributed through the year than is the case with a natural lake overflowing. Health impacts of man-made lakes are due to both the process by which they are created and the ways in which they are subsequently operated. These are best considered separately, but it has to be remembered that resources for disease control and particularly for health care are much more readily available in the construction phase than thereafter, and the construction phase provides an opportunity to create a sound health care infrastructure which will persist for many years following the filling of the reservoir.

It is important when planning a reservoir to consider the whole catchment and the effects that its construction and operation will have upon the water throughout the catchment. Often the indirect effects of reservoir construction will be felt for a long way downstream. Where reservoir

creation leads to upstream flooding of inhabited areas, adequate provision is critical for the displaced population. Historically, those people have fared very badly out of the creation of man-made lakes. Enough is known from earlier experience to avoid many of these problems, but usually there are still inadequate resources provided at the planning stage and consequently this difficult and complex operation is very detrimental to the displaced people.

Whenever a man-made lake is planned, it is essential at an early stage in the planning process to undertake a health opportunity assessment on a scale appropriate to the size of the project. Historically, such matters were not considered until relatively recently. Then the concept of an environmental impact assessment of water resources development was introduced and, mainly from evidence of schistosomiasis spread, this was developed into a health impact assessment. More recently it has been realized that not only should reservoir creation not lead to an increase in the local endemic diseases nor to outbreaks of epidemics, but also it provides an admirable opportunity to improve the health and health care facilities for the population who will be living around the lake.

This entry will focus particularly upon communicable diseases. In relation to lakes and reservoirs it is possible to classify communicable diseases by the biological nature of the causative agent, but it is more helpful to those outside the health sector to consider the different modes of transmission, because these point to the environmental modifications which can reduce transmission and which are usually the responsibility of those outside the health sector.

Water-related disease transmission

There are four main categories of transmission of water-related communicable diseases.

1. *Truly Waterborne Diseases*. These are infections where the causative organism is transmitted from one person to another by the water route. These are the concerns particularly of those providing drinking water for domestic use and where the aim will be to reduce the chance of disease being conveyed to people who drink the water. Disease transmission by this route requires both pollution of the water by a person or an infected animal and subsequent survival of the organism in the water with or without multiplication, and then for people to ingest the organisms. The classical diseases in this category are cholera and typhoid and the causes of watery diarrheas, and also *Shigella* or bacterial dysentery. As with most infections involving water bodies, transmission will largely take place at the water's edge, where pollution by excreta may occur and people collect domestic water and bathe, or near to it in shallow water offshore or wetlands near to the shore. The smaller the water body, the greater is the risk. Therefore, the risk of ingesting enough organisms to transmit the disease is relatively low in large lakes, especially

away from the shore, because of the huge dilutions involved. By contrast, small pools and ponds can very easily become polluted and if used as a source of drinking water may well pass on these organisms. Although both natural lakes and many reservoirs are used deliberately as a source of drinking water for substantial communities, the water will usually be treated before it reaches the distribution system of pipes and taps. Space does not permit an extensive discussion of water treatment. Most commonly, when pollution occurs and leads to large outbreaks of disease it is because of contamination close to or within the transmission system from the lake to the users and particularly when the water treatment works is not functioning satisfactorily. Where water is collected by individuals from poorer households around the lake there will be a risk, usually less for a large water body.

2. *Water Washed Transmission of Diseases.* It has been found that, for many of the diseases once thought primarily to be transmitted through drinking water, the availability of adequate water for personal cleanliness, accompanied by suitable hygiene behavior, such as the use of soap for hand-washing after defecation, can greatly reduce the incidence and severity of diarrheal diseases. It is easier for those living close to the shore of a lake or reservoir, even if they are having to use untreated water from the margin, to obtain adequate water for washing and personal use, and so to this extent the hazard of diarrheal disease and of skin infections and the blinding eye disease, trachoma, is reduced for such people. By contrast, in other respects, living very close to water may increase the risk of vector-borne diseases. It must be remembered that where villages are sited away from large water bodies it is critical to provide adequate water right to the village, preferably taken from some distance away from the shore of the lake, even if it is not possible to treat the water properly for domestic use.
3. A group of infections called *Water-Based Diseases* are of great importance in relation to lakes, and even more so in relation to reservoirs in many parts of the tropics and subtropics. These diseases are where the causative organism has a life cycle, part of which is spent inside people and part in organisms that live in the water. The most important of these are the various trematode or flatworm infections (sometimes called fluke infections), which have stages in water snails, and in particular the several forms of schistosomiasis, described below; but there are also rarer infections, which pass from people to snails, and then from the snails into what are called second intermediate hosts, usually fish, and people become infected by eating the fish inadequately cooked.
4. Water bodies act as breeding sites for *Water-Related Insect Vectors of Disease* in warm-climate countries. The mosquitoes predominate as vectors and the key diseases transmitted are arbovirus fevers and malaria (see below). The majority of mosquitoes breed

preferentially in small water bodies and in shallow wetlands such as rice fields, but the edges of lakes and still more of reservoirs provide breeding habitats for several important vectors. These may be in fringing vegetation or in puddles left by falling water levels of reservoirs. A specialized group of floodwater mosquitoes have resilient eggs which can survive in sand near the high watermark for long periods, rapidly hatching when the next inundation occurs, sometimes several years later. These floodwater mosquitoes carry certain arboviruses in particular.

Other insect vectors of human disease associated with reservoirs are *Simulium* vectors of the worms which cause river blindness or onchocerciasis. They are small biting flies whose larvae, needing highly aerated water as a habitat, especially occur on dam spillways and in torrential feeder streams for the reservoir. The tsetse flies, *Glossina*, that transmit sleeping sickness (trypanosomiasis) in Africa include some species that bite in tree-shaded fringes of lakes, most notably Lake Victoria.

Some diseases that fall into categories 3 and 4 are of particular relevance and are considered in more detail.

Diseases particularly transmitted in lakes and reservoirs

Schistosomiasis

Schistosomiasis is the dominant problem associated particularly with man-made lakes, although transmission takes place also in natural lakes in parts of Africa, Latin America, and southeast Asia in particular. All the human schistosomes have a basically similar life cycle. The parasites live in the blood vessels of their human host, and lay eggs which escape in the excreta, whether urine or feces depends upon the species of *Schistosoma* involved. If the excreta pollute the water the eggs of the schistosome hatch out to set free a microscopic larva, or miracidium, which swims about for some hours. If it encounters a suitable species of water snail, this larva will penetrate the tissues of the snail and infect it. Over the next month, the parasite will develop within the body of the snail, gradually destroying many of its internal organs, and after some weeks the larval schistosomes will emerge and swim about in the water. This will happen daily for the rest of the snail's life. If people are wading in the water, the schistosome larva, or cercaria as it is called, will rapidly attach to their skin and then bore through the skin into the blood vessels beneath. The cercariae will be swept to the lungs and subsequently other organs of the body, where they will undergo development. The sexes of *Schistosoma* worms are separate, and when they mature they migrate to the blood vessels of the bladder and intestinal walls, pair, and the female will begin laying eggs on a substantial scale. *Schistosoma* worms are very long-lived and it has been found that people who have become infected and then moved away from the chance of further infection may go on passing eggs in substantial numbers for decades. Many of the *Schistosoma* eggs do not

successfully escape from the host and they are the cause of much damage to the tissues of the person who is infected.

There are five main species of *Schistosoma* that infect people. *Schistosoma haematobium* lives in the blood vessels around the bladder of the infected person, and the eggs that are laid by the worm gradually find their way from the blood vessel through into the lumen of the bladder, so that they escape when the infected person urinates. Many eggs accumulate and die in the tissues of the ureters and bladder. Fibrosis and inflammation around the eggs leads to damage to the bladder wall and ureters and also encourages the formation of urinary stones or calculi. Damage may occur to the kidneys as a result of obstruction to the flow of urine. In very heavy infections, as used to be observed particularly in Egypt, cancer of the bladder is a major complication. *S. haematobium* is found throughout much of Africa and in parts of Western Asia. It is transmitted by aquatic snails of the genus *Bulinus* with a rather low spire, some of which can aestivate in the mud of desiccated pools during the dry season.

S. mansoni has a more restricted distribution in tropical Africa and the Nile basin, also the Arabian Peninsula, South America, and the Caribbean. The aquatic intermediate host snails are flat spiral snails of the genus *Biomphalaria*. The adult worms live in the blood vessels around the large intestine, so that the eggs they lay pass through its wall and are shed in the person's feces. The pathological effects are mainly due to many eggs that do not escape being carried in the portal vein to the liver, where they get impacted and an inflammatory reaction occurs around them. Eventually the eggs are destroyed, but in some people, the fibrous tissue left behind by vast numbers of eggs eventually causes extensive and potentially fatal liver fibrosis. *Schistosoma intercalatum* in West Central Africa behaves similarly to *Schistosoma mansoni*, though its eggs resemble those of *Schistosoma haematobium*. *Schistosoma japonicum* of East Asia and parts of SE Asia has a similar pathology to *S. mansoni*, but far more eggs are laid by each female and the chance of severe disease is much greater in *S. japonicum* infections. *Schistosoma mekongi* is very similar and occurs, as its name suggests, chiefly in the Mekong Valley. *S. japonicum* has a small amphibious snail of the genus *Oncomelania* as the intermediate host, whereas *S. mekongi* has an aquatic snail, *Tricula*.

Schistosomes are par excellence the parasites associated with water resource developments. Much is known about the biology of the varied local species of intermediate host snails, so that the risks of schistosomiasis can be predicted approximately at the planning stage, but not with precision. Thus, when the Volta (Akosombo) dam in Ghana was being constructed, a schistosomiasis problem was foreseen for the lake, but the species of snail and the type of schistosomiasis were unexpected: there was a large *S. haematobium* problem imported by migrant fishermen and spread by dense *Bulinus* populations. However, the later downstream dam at Kpong, which is kept at

a relatively constant water level perennially, supported snails transmitting both schistosome species. Jobin (1999) has pointed out that this is replicated in some other pairs of dams in Africa, reasoning that *Bulinus* thrives in the upper reservoir in spite of large annual fluctuations in the water level whereas *Biomphalaria* is also present in the lower reservoir which is kept at a relatively constant level. A few species of *Biomphalaria* can live in deep water and have been responsible for offshore schistosomiasis transmission.

A biologically related problem of temperate climate reservoirs involves those schistosomes with birds as their definitive hosts. Sometimes very large numbers of water snails become infected with their developmental stages and huge numbers of cercariae are shed. These are able to penetrate human skin but not to survive further, and there is an inflammatory response to the dead cercariae. This leads to outbreaks of a rash called "schistosome dermatitis" among lake bathers in the late summer in the USA, UK, and many other countries.

Malaria

In the case of malaria, the most important vector-borne disease globally, the consequences of water resource development depend heavily on the baseline level of malaria transmission and the type of water development. The infection is transmitted by female mosquitoes of the genus *Anopheles*, which become infected by feeding on the blood of people with malaria. The parasites develop in the mosquito, migrate to its salivary glands after 1–2 weeks, and then are inoculated into other people when the mosquito feeds again. The parasites then multiply repeatedly, first in the liver and then in the human blood cells, the latter on a 2–3-day cycle so that the patient gets an intermittent fever which worsens as parasite numbers increase in the blood. In nonimmune people, death may follow from disturbance to the brain (cerebral malaria) in children and adults and from anemia in infants if they are suffering from *falciparum* malaria (of the four species of malaria that commonly infect man, this causes by far the most severe illness and is especially prevalent in Africa). At low levels of transmission prior to the development, as in many parts of India, the creation of a reservoir, and particularly one that feeds an irrigation scheme, has historically been followed by epidemic malaria. By contrast, in parts of West Africa with very heavy transmission of malaria already taking place, creation of a reservoir or irrigation scheme may greatly increase the abundance of vector mosquitoes but with little or no increase in clinical malaria. This is because the existing level of transmission is so high that children are already infected with malaria from early infancy, and acquired human immunity regulates the levels of disease observed. Indeed, in some parts of Africa the creation of irrigated rice agriculture appears to decrease the malaria level somewhat; this is sometimes known as the "paradox of the paddies" and it is not yet fully understood.

Importance of disease due to large dams

The infectious and communicable disease burden due to water resource development has been assessed for several key vector-borne diseases, primarily in relation to the larger dams and reservoirs. Malaria and schistosomiasis are greatly affected by surface water storage.

The effect will vary greatly with the baseline endemicity and local vector species, so that, for example, four times larger a percentage of schistosomiasis incidence can be ascribed to dams in South East Asia than in Africa, although the actual number of people involved is far greater in Africa south of the Sahara. Meticulous calculations have been made by Kaiser, Utzinger, and colleagues in a series of systematic reviews of the key vector-borne diseases, and the results are summarized in Table 1. Globally it appears that some 42 million people are at risk of schistosomiasis from big water storage dams, of whom 10 million are infected (Steinmann et al., 2006), while 18 million are at risk of malaria as a consequence of water storage in large dams (Keiser et al., 2005).

Environmental measures of disease control

There is sufficient knowledge to propose interventions against many pathogens and vectors but, as with most control by environmental means, interventions need to be appropriate for the local organisms and human activities and also to be maintained scrupulously, which is operationally not easy. Engineered environmental changes often need to be accompanied by changes in human behavior. Structural changes to prevent disease transmission are usually called environmental modification, while recurrent management issues such as clearing vegetation, sluicing, and regulating salinity are called environmental manipulation.

The water level of many lakes and all reservoirs tends to vary on an annual cycle. The extent of this variation, along with the slope of the shoreline and the rate of drawdown, will substantially affect populations of vector insects and intermediate host snails.

Because the vast majority of the health effects of lakes and reservoirs are determined by events close to the edge of the impoundment, its nature is of great importance.

A steep shore that is unsuitable for human waterside activities, lacks vegetation and descends sharply below the water level will be most conducive to health. Where the shoreline is gently sloping and supports emergent and floating vegetation it provides a habitat for snails and mosquito larvae, especially where wave action is reduced. In Africa, fringing trees may need clearing or their lower branches removing to deter tsetse flies from biting. Human settlements should be sited away from the shore (preferably over 2 km) but water piped to them and sanitation facilities provided. In tropical areas, the aim will be to minimize contact between the people and the reservoir edges, such as by constructing jetties and cleared landing places, although, particularly among fishing communities, substantial water contact may be inevitable. Where schistosomiasis is endemic, infection may well occur, although the worm burden and so the chance of serious disease may be greatly reduced by these environmental and behavioral measures. There is now satisfactory chemotherapy available and a regular cycle, perhaps annually, of testing and treatment for schistosomiasis may be needed. Although molluscicides are available, their sustained use in lakes and reservoirs (apart from small pools and night storage ponds for irrigation) is impracticable.

Deliberate variation of the water level for disease control has been used for some reservoirs to control schistosomiasis and malaria. In the pre-1939 "golden age" of environmental management for vector control, just prior to the introduction of residual insecticides, particular attention was paid to varying the water level of reservoirs in a controlled way, especially in the USA, deriving from the experience of the Tennessee Valley Authority in malaria prevention on impounded waters (USPHS and TVA, 1947). The water level in medium-scale reservoirs can be rapidly lowered either by manual control of the sluice gates or by an automatic siphon device. By careful manipulation of a series of dams on the Tennessee River it was possible to raise the water level transiently to flood height, so stranding flotsam and floating vegetation that tended to harbor vector mosquito larvae. Subsequently, rapid dropping of the water level was able to strand the larvae of *Anopheles quadrimaculatus*, the local malaria

Health Aspects of Lakes and Reservoirs, Table 1 Schistosomiasis and malaria risk from water storage in large dam reservoirs

WHO Region	Schistosomiasis			Malaria	
	At risk from big dams Millions	% of total risk from big dams %	Estimated infected from big dams Millions	Number of big dams Number	People at risk from big dams Millions
<i>Africa S of Sahara</i>	28.71	5.1	9.62	525	3.07
<i>Latin America</i>	1.22	3.4	0.06	1,449	0.48
<i>Middle E and N Africa</i>	2.35	1.7	0.29	812	2.46
<i>SE Asia and W Pacific</i>	10.09	21.7	0.23	6,405	12.33
World	42.36	5.4	10.20	9,191	18.34

The data are derived from Keiser et al. (2005) and Steinmann et al. (2006)

vector, and marshy areas dried out. The malaria vector bred close to the shoreline during May to September. From July, the level gradually recedes some 3 cm per week, but superimposed on this are forced fluctuations of 30 cm approximately weekly which repeatedly strand each generation of the mosquito eggs and larvae. The water regime also kept the larvae clear of emerging vegetation which provides cover for them, and helped the breeding of larvivorous fish. This highly successful approach to malaria control depended upon joint planning by engineers and vector biologists, the particular ecological characteristics of the North American malaria vectors, and the availability of water in the river to allow fluctuation of the water level. The approach has also been used against *Anopheles culicifacies* in South Asia. However, as with most environmental control methods, this is species-specific. Any attempt to use it against puddle-breeding mosquitoes in the African tropics, around reservoirs too large for rapid oscillations of level and with very shallow sloping edges, would be worse than useless: the rate of water level fall would be slow and generate extensive breeding sites for *Anopheles gambiae*, the world's most effective malaria vector, and do more harm than good.

Water level fluctuations have also been considered as a way to strand aquatic snails in Africa, but the estimated drawdown rate required, around a meter per day, is greatly in excess of what seems feasible operationally. Changes in discharge flow rates have also been recommended for *Simulium* control, but this appears speculative, unless the spillway can be dried out. More successful in one site, the origin of the White Nile from Lake Victoria, was positioning of a narrow pipe down through the dam wall so that liquids could be added to the outflow from the sluices. Insecticides were poured down at regular intervals; the turbulence reduced the insecticide particle size down to 1 μ diameter. This size of particle was raked out of the water by the feeding habits of the *Simulium* larvae which were thereby poisoned selectively. Moreover, when this came to an end after some years, it appears that the *Simulium* species that re-invaded the empty ecological niche was of a type that did not bite humans.

Where malaria vectors and other vector mosquitoes are not amenable to environmental control by water level or shoreline manipulation, or where there is residual malaria after they have been applied, other methods need to be used in addition for both prevention and prompt treatment. These include use of insecticide-treated mosquito nets if the vectors are nocturnal and rest indoors, house screening, possible residual insecticide spraying, and use of repellents, as well as sufficiently accessible dispensaries or health centers stocked with locally approved antimalarial medicines for treatment, as severe malaria is a medical emergency requiring immediate action.

Reservoir construction and early filling

There is now much published work on the health hazards of major water storage reservoirs (Stanley and Alpers,

1975; Jobin, 1999). Planning (stage 1) to construct a dam, and even the rumor that this might happen, will lead to a set of social and environmental changes with health consequences of an unplanned as well as an intended nature. The construction phase (stage 2) will greatly intensify these, as there will be immigration of workers, of those hoping to provide services for the workers, and often the beginnings of a health infrastructure. The health problems of transient labor predominate: trauma, sexually transmitted and respiratory infections, and outbreaks of locally endemic diseases if the workers are from a non-endemic area. Funds for infrastructure may enable good facilities for the longer term. The local people displaced from the inundated area almost invariably suffer from inadequate support and lack of planned movement to a suitable site. These indirect health consequences of creating water storage matter, and also provide health opportunities.

The early period after filling the reservoir (stage 3) may see complex biological changes such as rotting forests, explosions of insects, fish, fishermen, and shoreline vegetation with vector habitats being created, leading to outbreaks of schistosomiasis and malaria (in areas of previously low transmission), with gradual progression to a steady state (stage 4) which may or may not include a higher level of health hazards than before. Stages 1–3 comprise a key period or “Chronotone” lying between the original state of the landscape and the final relatively steady state of the mature dam and reservoir (Bradley, 2004). The terminology is by analogy with the term ecotone, which is the area in space that lies between two types of ecosystem whereas the chronotone is an equivalent interval in time rather than space. It includes the structures, water and adjacent land, the ecology, settlement, use and social conditions. Many of the changes that occur during the chronotone are predictable, and others not, so there is a need both to plan the management of expected health hazards and to monitor the situation. It is a key time to invest effort in order to reap long-term reductions in health hazards. While this is also true of small impoundments, the strategy needed is different from that appropriate for large reservoirs. For a big dam, such as that for the Volta Lake, Ghana, the chronotone may last for around two decades.

Small reservoirs

Methods to reduce the health hazards of large reservoirs are well studied, even if often ignored, but those for small dams are less clear, requiring choice appropriate to the locally relevant pathogens and further research attention.

Small multipurpose reservoirs, “tanks” and “dams” are probably collectively more important for health than are large dams, making up in numbers what they lose in capacity. In part of Northern Nigeria there were over 700 in a limited area. Worldwide, in 2001 it was estimated that there were 40,000 large dams and over 800,000 small reservoirs (Keiser et al., 2005), although the last figure is

probably a substantial underestimate. Multiple small reservoirs pose different problems from big dams. Formal control over them is weak, and is exerted at local level by local government and community pressure. The users need to be convinced if health measures are to be implemented and maintained. The various health risk issues have to be balanced against the different uses to which the water will be put. General rules are less applicable and flexible local inputs are needed. Resources are, however, much more limited and many small dams pose major health hazards.

Measures to control the health hazards of small dams are site-specific, but may include avoiding the need to enter the water, by provision of pumps, cattle troughs (but with adequately drained surrounds), sites for laundry and canoe landing stages. These will reduce schistosomiasis risk. Fencing may be used to prevent access of livestock and consequent pollution, and steep edges to the pool deter emergent vegetation and reduce mosquito breeding (although they may create a drowning risk to children unless fenced), while stocking with appropriate small fish may reduce mosquitoes further. The floating fern *Azolla* will also deter mosquito breeding (especially of anophelines) once surface coverage exceeds 90%, which may or may not be acceptable to users. It is difficult to prevent all pollution of surface waters and some form of post-storage treatment is, if possible, needed for drinking water. In the tropics, sanitation is best directed toward pathogen reduction, rather than relying on water treatment to achieve this.

Conclusion

Several broad principles should govern the approach to health issues in developing impoundments of water, whether small or large. These include considering health issues at all stages of the project, from initial plans and design right through to operation and management.

Early advice should be sought from public health experts, particularly those who have worked in the area of the proposed reservoir for many years, both medical biologists and communicable disease epidemiologists. In the case of a large development, an expert epidemiological team will need to make a health opportunity assessment. The issues should be addressed from a co-ordinated but interdisciplinary viewpoint, at all stages.

Research has been concentrated on health hazards of large dams, but in spite of some excellent local studies, work on smaller water storage reservoirs is relatively neglected. More work is needed on these problems, not only in relation to health but also into linked aspects of agriculture, livestock watering, and conservation.

Whatever the scale of water storage, planning for health hazard reduction needs to be undertaken well before the development and construction of new storage. The chronotone, or period of rapid change around the development that is crucial for effective long-term action, is a period of great opportunity to improve health.

The literature on reservoirs and disease transmission is chiefly from the last three decades of the twentieth century when many large dams were built, especially in the tropics, and the two best books are Stanley and Alpers (1975) and Jobin (1999), the former for its broad scope and Jobin for detail on selected areas from a control viewpoint. The water-related disease classification is to be found in White et al. (1972). Keiser and Utzinger's papers have the best estimates of the effects of water development on malaria and schistosomiasis. Birley's (1991) guidelines can be downloaded from the WHO website, as can Bradley and Bos (2010) from the SIWI website.

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Cross-references

[Brownification of Lakes](#)
[Cyanobacteria \(Blue-Green Algae\)](#)
[Dam Failures: Impact on Reservoir Safety Legislation in Great Britain](#)
[Dams, Flood Protection, and Risk](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Gippsland Lakes](#)
[Hazards](#)
[Large Dams, Statistics and Critical Review](#)
[Light and Primary Production in Lakes](#)
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[Reservoirs, Multipurpose Use of Small Reservoirs](#)
[Three Gorges Project on the Yangtze River in China](#)
[Trophic Lake Classification](#)
[Urban Lakes and Ponds](#)
[Water Framework Directive](#)
[Water Quality for Drinking: WHO Guidelines](#)
[Water Quality in Lakes and Reservoirs](#)

HYDRODYNAMICS AND CIRCULATION OF FJORDS

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Introduction

Fjords are narrow and deep inlets, carved by glacial processes, with a sill in the mouth. They are typically strongly stratified, often with three clearly distinguishable water masses. The surface water has often reduced salinity due to local freshwater supply. The stratification of the intermediary water, between the surface water and the basin water, continuously mirrors the ever-changing stratification of the coastal water outside the mouth but with some phase delay. The basin, below the sill level, contains the basin water which is the densest water that occurs above sill level in the coastal area, i.e., outside the fjord. Water masses and some physical processes and modes of circulation in fjords are indicated in [Figure 1](#).

Currents in a fjord are generally forced both inside and outside the fjord. The local wind in the fjord forces surface currents that are approximately in the wind direction and with a speed that is a few percent of the wind speed. The wind drift converges toward the shores whereby baroclinic horizontal circulation, often encompassing the upper layers of the whole fjord, is generated. The wind also drives vertical mixing of the surface layer and if there is local freshwater supply to the fjord, wind mixing will sustain so-called estuarine circulation leading to outflow of brackish surface water and inflow of seawater. Remotely forced circulation will proceed in a fjord even under calm conditions. One differentiates between baroclinic circulation that varies vertically and barotropic circulation with uniform velocity in the whole water column. Remotely forced circulations are driven by horizontal pressure gradients, due to differences in vertical

stratification and sea level, respectively, between the fjord and the area outside the fjord.

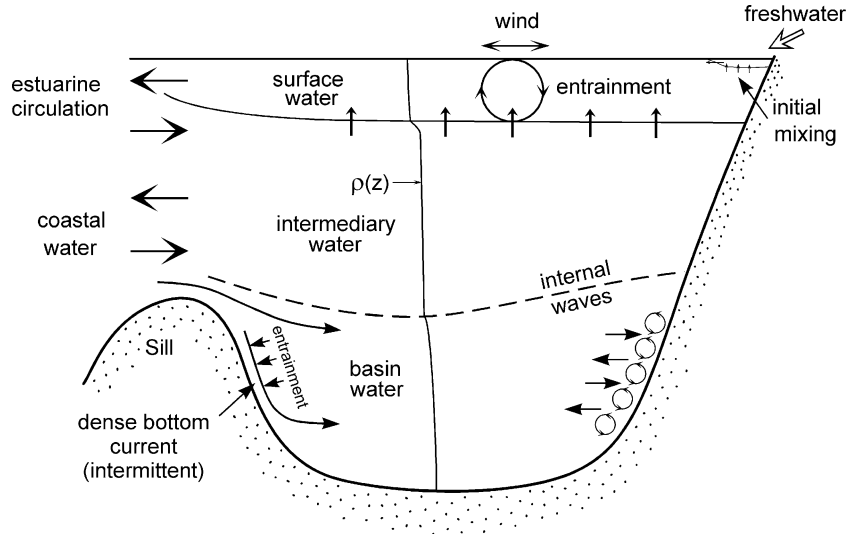
In this entry, currents due to various modes of circulation are discussed with focus on fundamental dynamic balances and simple formulas that can be used to make first-order estimates of the flow through the mouth and also within fjords. The water exchange with the coastal water is coupled to various modes of forcing and the following externally forced processes and circulation modes are discussed here.

- Intermediary circulation forced by density variations outside the fjord (Section [Intermediary Circulation Forced by Density Variations in the Coastal Water](#))
- Barotropic tidal circulation forced by sea level variations outside the fjord (Section [Barotropic Tidally Driven Circulation](#))
- Estuarine circulation forced by local wind mixing and freshwater supply (Section [Estuarine Circulation](#))
- [Generation of internal tides and jets at sills](#)
- Vertical mixing in fjord basins, ultimately powered by tides and the local wind (Section [Vertical Mixing in Fjord Basins](#))
- Exchange of basin water (below sill level) forced by turbulent mixing (Section [Exchange of Basin Water](#)).
- In addition there is also internally forced wind drift and wind-driven fjord-scale circulation and surface and internal seiches (Section [Wind Drift and Related Phenomena](#)).
- Application of hydrodynamics to fish farming (Section [Hydrodynamics of Fjords Applied to Fish Farming](#)).
- A short summary concludes the entry (Section [Summary](#)).

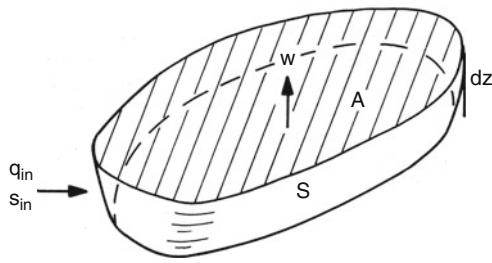
The aim of this entry is to give an overview of the hydrodynamics of fjords including general modes of circulation with emphasis on basic dynamics. Excellent reviews of the physics of fjords have been written by Gade and Edwards (1979) who concentrated on deepwater renewal, by Farmer and Freeland (1983) who covered several aspects and recently by Inall and Gillibrand (2010) who covered recent contributions to the physics of fjords, and Cottier et al. (2010) who reviewed the physical oceanography of Arctic fjords.

Stratification changes in small fjords due to water exchange and mixing

The waters of many fjords may be treated as 1D because horizontal gradients are much smaller than vertical. The 1D vertical advection–diffusion equation for salinity (temperature, etc.) is then an appropriate starting point for descriptions of large-scale circulation. Consider a horizontal slice (slab) of a fjord centered at the depth z - ([Figure 2](#)). The slice has thickness dz , horizontal surface area $A(z)$, volume $V(z) = A(z)dz$, and salinity $S = S(z)$. Inflow/outflow through the fjord mouth introduces a flow $q = q(z)$ into and out of the fjord which in turn introduces vertical advection of velocity $w(z)$ through the



Hydrodynamics and Circulation of Fjords, Figure 1 Water masses, physical processes, and circulation modes in fjords. The vertical density distribution is shown by $\rho(z)$. Mixing in the basin water occurs essentially at the bottom boundaries.



Hydrodynamics and Circulation of Fjords, Figure 2 Definition sketch for the vertical 1D-model of a fjord basin. The vertical z -axis is directed upward.

horizontal boundaries of the slab. The salinity of water flowing into the slab by the flow $q(z)$ is $S_{in}(z)$. For horizontal flow out of the slab (q is negative) S_{in} equals $S(z)$. Salt is also transported through the horizontal boundaries of a slab due to vertical turbulent diffusion.

Conservation of salt in the slab is described by

$$\frac{\partial S}{\partial t} = \frac{1}{A} \left(\frac{\partial}{\partial z} \left(A \kappa \frac{\partial S}{\partial z} \right) - \frac{\partial}{\partial z} (wAS) + qS_{in} \right) \quad (1)$$

Conservation of volume requires

$$q - \frac{\partial}{\partial z} (wA) = 0 \quad (2)$$

Combination of [Equations 1](#) and [Equations 2](#) gives the following equation for the rate of change of salinity of a slab:

$$\frac{\partial S}{\partial t} = \frac{1}{A} \left[\frac{\partial}{\partial z} \left(A \kappa \frac{\partial S}{\partial z} \right) - wA \frac{\partial S}{\partial z} + q(S_{in} - S) \right] \quad (3)$$

Similar equations may be derived for temperature T and other conservative scalars. If nonconservative substances are considered, e.g., dissolved oxygen, plant nutrients, and various tracers, there should also be sink/source terms in the equations corresponding to [Equations 1](#) and [Equations 3](#). The vertical advection–diffusion model above is discussed in more detail in Stigebrandt (1987, 1990).

If the diffusive term may be neglected compared to the advective terms, [Equation 3](#) simplifies to

$$\frac{\partial S}{\partial t} = \frac{1}{A} \left[-wA \frac{\partial S}{\partial z} + q(S_{in} - S) \right] \quad (4)$$

For depths where there is outflow, $S_{in} = S$ and salinity changes only due to vertical advection. The vertical speed can then be written as

$$w = -\frac{\partial S}{\partial t} / \frac{\partial S}{\partial z} = -\Delta z / \Delta t. \quad (5)$$

The vertical speed w can thus be estimated by the vertical distance Δz that an isohaline (or isothermal) surface moves during the time Δt . For the following example, it is assumed that $\partial S / \partial z$ is negative. With outflow from the upper layers (and inflow to lower layers) w is positive (upward motion) and $\partial S / \partial t$ is positive. With outflow from lower layers, w is negative and $\partial S / \partial t$ is negative. The expression for w becomes more complicated for depths where there is inflow, cf. [Equation 4](#). The total outflow Q_{Out} can easily be estimated from vertical integration of [Equation 2](#):

$$Q_{Out} = \max |Aw| \quad (6)$$

Equations 4, Equations 5, and Equations 6 are typically applicable to the intermediary layer where vertical diffusion usually contributes much less to temporal changes than vertical advection due to intermediary circulation, described in Section “Intermediary Circulation Forced by Density Variations in the Coastal Water” below. They can also be applied to study exchange of basin water by a dense bottom current using continuous observations of the vertical stratification in the basin.

In periods lacking inflow of new basin water, salinity in the basin water changes only due to vertical mixing and Equation 1 may be simplified as follows:

$$\frac{\partial S}{\partial t} = \frac{1}{A} \left[\frac{\partial}{\partial z} \left(A \kappa \frac{\partial S}{\partial z} \right) \right] \quad (7)$$

In this case, horizontally averaged values of κ may be estimated from horizontally averaged vertical profiles observed at two different occasions. Vertical integration of Equation 7 from the greatest depth $z = d$, where there is no diffusive flux of mass (through the sea bottom), to some level $z = u$, gives the following expression for the vertical diffusivity at the level $z = u$:

$$\kappa_{z=u} = \frac{1}{\left(A \frac{\partial S}{\partial z} \right)_{z=u}} \int_b^u \frac{\partial S}{\partial t} A dz \quad (8)$$

This equation may be used to compute κ at $n-1$ levels if there are n levels of observations of $S = S(z, t)$. This method, the so-called budget method, to estimate horizontally averaged values of κ is described at length by Gade (1970) and Gargett (1984). The latter author examined in detail various observational methods of obtaining the vertical diffusivity. She concluded that careful use of budgets of conservative scalars is the only unequivocal method to determine vertical diffusivity. Application of the budget method to cases where the small-scale turbulence is confined to a thin layer near the bottom (boundary mixing) is discussed in Stigebrandt (1976). The budget method to estimate the vertical diffusivity has been applied to numerous fjord basins (see Section Vertical Mixing in Fjord Basins).

Intermediary circulation forced by density variations in the coastal water

Density variations outside a fjord cause horizontal pressure gradients between the fjord and the area outside the fjord. These drive currents through the mouth that tend to adjust the stratification in the fjord to the stratification outside the fjord (Pettersson, 1920). The circulation driven by this mechanism (baroclinic pumping) is called intermediary circulation because it is most apparent in the intermediary layer. It is well known that intermediary circulation may exchange the water above the sill in fjords which explains rapid shifts in pelagic ecology, e.g., Lindahl and Hernroth (1988) and Matthews and Heimdal (1980). It is suspected that intermediary circulation

strongly contributes to rapid circulation of warm subtropical waters in a glacial fjord in Greenland (Straneo et al., 2010). Intermediary circulation is described in Svendsen (1980), Holbrook et al. (1983), and Aure et al. (1996). Arneborg (2004) demonstrated that the amplitude of the annual temperature cycle beneath the surface layer is smaller in the Gullmar Fjord than outside, showing that intermediary circulation is damped as it proceeds into the fjord.

Time-dependent intermediary water exchange through a fjord mouth was computed in Stigebrandt (1990) using a numerical fjord model. The flow was forced by the synoptic horizontal baroclinic pressure gradient in the mouth as determined from the vertical density profiles on both sides of the mouth. Engqvist and Omstedt (1992) made similar computations of intermediary water exchange of a fjord in the Baltic proper. Coupled fjord-ocean numerical models have been used to simulate coast-fjord water exchange driven by density variations in the coastal water, e.g., Klinck et al. (1981), Asplin et al. (1999).

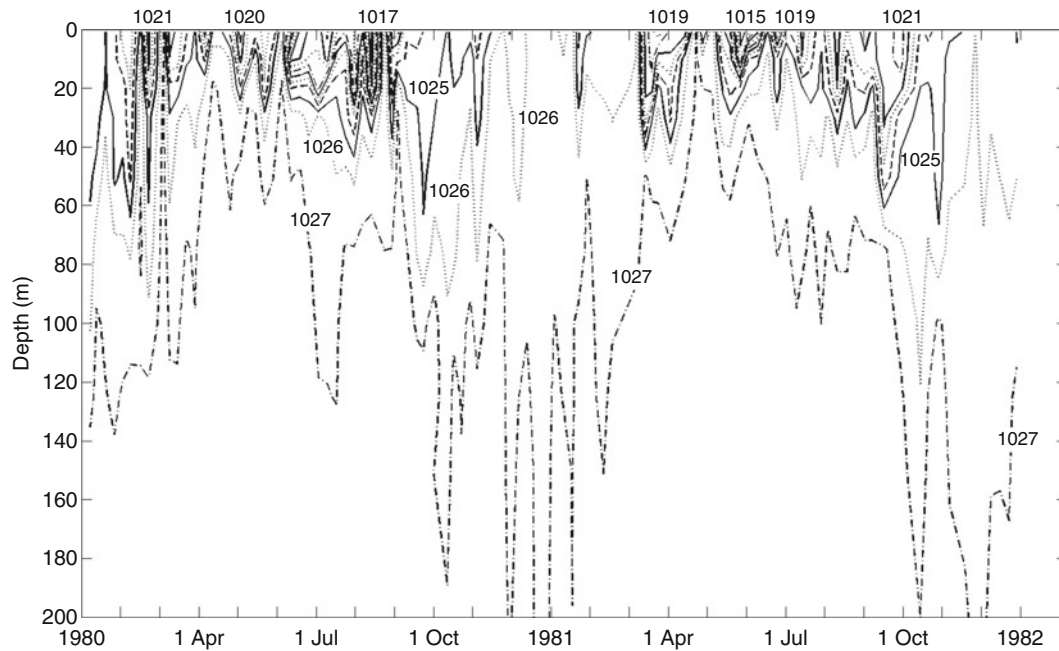
Estimates of the water exchange of many Scandinavian fjords by the box model “Fjordenv,” described in Stigebrandt (2001), show that intermediary water exchange often is larger than the sum of tidal and estuarine water exchange. This is in particular true in fjords with deep mouths.

Density variations in the coastal water

Variations of the vertical density distribution at a coastal site may be caused by variations of the regional wind causing convergence and divergence at the coast and thereby upwelling and down-welling. However, variability of the vertical density distribution at a coastal site may also be caused by advection of horizontal density gradients along the coast.

In many coastal areas, there are observational series that may be used to compute the variability of the density field in coastal water. However, observations are often made with rather low frequency. This means that it is not possible to estimate the correct spectral distribution of the variability because variability at frequencies higher than the Nyquist frequency (i.e., half the observational frequency) will falsely be attributed to lower frequencies. This well-known effect is called aliasing. Here we present the variability at the hydrographical station Lista localized just outside the southwestern tip of Norway (N 58°05'; E 6°32'). Observations started in 1942 and are typically carried out twice a month. About 1,750 vertical profiles have been taken since the start. Lista is one of eight coastal stations regularly monitored by Institute of Marine Research in Bergen. The isopleth diagram in Figure 3 shows the density field observed at Lista in the years 1980 and 1981 when the observational frequency was maximum due to a research program. This plot is based on 98 profiles.

The variance at each observational depth of a hydrographical time series with low temporal resolution, $\text{Var}(\text{tot})$, is here formally partitioned into three parts,



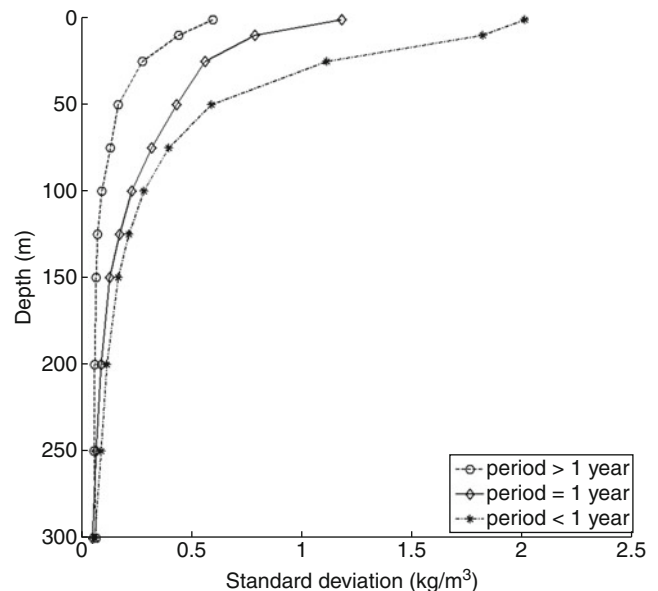
Hydrodynamics and Circulation of Fjords, Figure 3 Observed density field during 1980 and 1981 at Lista. It is readily seen that the variability of the density field cannot be described as only due to vertical advection (by upwelling and downwelling). The contribution by horizontal advection of horizontal gradients is obviously large.

namely, the variance for periods less than 1 year, $\text{Var}(<1)$, the variance for the period exactly 1 year $\text{Var}(=1)$, and the variance for periods longer than 1 year $\text{Var}(>1)$, thus

$$\text{Var}(\text{tot}) = \text{Var}(<1) + \text{Var}(=1) + \text{Var}(>1) \quad (9)$$

The partition is done as follows. One first computes the total variance, $\text{Var}(\text{tot})$, using all data. Thereafter one computes the mean annual cycle described by monthly means and computes the variance of this cycle, $\text{Var}(=1)$. The monthly means are then subtracted from the original data series. The resulting series does not contain the mean annual cycle. Then one computes annual averages. The resulting series only contains long-term, sub-annual variability and the variance of this, i.e., $\text{Var}(>1)$ is computed. Using Equation 9, the variability of short-term fluctuations is then given by $\text{Var}(<1) = \text{Var}(\text{tot}) - \text{Var}(=1) - \text{Var}(>1)$. Of course, this is only approximately correct due to aliasing as discussed above.

The results of an analysis applied to the time series from Lista are shown as the standard deviation σ_p which is the square root of the variance (Figure 4). It can be seen that the variability decreases with depth. Short-term variability is greater than the variability of the annual density cycle but the difference decreases with depth. Sub-annual variability is substantially smaller than the other two components. However, as will be discussed in Section “Exchange of Basin Water” below, the variability at lower frequencies may be important since it may determine the



Hydrodynamics and Circulation of Fjords, Figure 4 Standard deviation of the density field at Lista has been partitioned into three period bands, see legend.

residence time of basin water in fjords where the rate of vertical mixing in the basin water is relatively weak.

By studying the variance around the monthly means at Lista, it is found that the largest variability in the upper

layers, from sea surface and down to about 25 m depth, occurs in summer and autumn. From 50 m depth and deeper, the largest variability occurs in autumn.

The variability of the density field at Torungen and Jomfruland outside the Norwegian Skagerrak Coast was observed during 1 year by Aure et al. (1996) using moored instruments. Observations were recorded every tenth minute to avoid aliasing. They found that about half of the variability occurs for periods of 1 month and longer. Periods of 1 week and shorter contribute about 25% of the total variance in the upper 20 m but the contribution decreases to about 10% at 70 m depth. Gustafsson and Stigebrandt (1996) described the horizontal distribution of the variability of the density field in Skagerrak using the ICES database.

A simple empirical model of intermediary circulation

The intermediary circulation was for a long time quite anonymous. A probable reason for this is that there was no simple model or formula to estimate it. Stigebrandt and Aure (1990) used the numerical model in Stigebrandt (1990) to compute the intermediary circulation Q_i in a spectrum of fjords driven by a 1-year-long series of weekly observed vertical density profiles obtained in the coastal water in Møre and Romsdal, Norway. From the model results, they derived the following empirical formula:

$$Q_i = \gamma \left(g B_m H_t A_f \frac{\Delta M}{\rho_0} \right)^{1/2} \quad (10)$$

Here γ is a nondimensional empiric coefficient that equals $17 \cdot 10^{-4}$. B_m is the width of the mouth, H_t the sill depth, A_f the horizontal area of the fjord at sea surface, g the constant of gravity, and ρ_0 a reference density.

As a measure of the forcing of the flow, they used ΔM , which is the standard deviation of the weight M of the water column from mean sea level down to sill level (kg m^{-2}). ΔM is estimated by vertical integration of the standard deviation of coastal water density $\sigma_\rho(z)$ from the sea surface down to sill level, thus

$$\Delta M = \int_0^{H_t} \sigma_\rho(z) dz \quad (11)$$

According to Equation 10 the forcing of the intermediary circulation is proportional to $\Delta M^{1/2}$. Note that Equation 10 should give the long-term mean of the intermediary circulation in a fjord. Inflow and outflow are equally large ($=Q_i$) since the circulation is baroclinic. For fjords with relatively narrow mouths, the current speeds may be quite large and in this case the flow may be hydraulically controlled and another formula should be used to estimate the intermediary exchange, see Stigebrandt (1990).

Aure et al. (1996) discussed the contribution from different periods to the forcing of the intermediary circulation

arguing that higher frequencies should be more efficient than lower frequencies. They suggested that ΔM should be modified to accommodate for the frequency dependence. It would probably be more relevant to use only the high-frequency part of the variance, at least for smaller fjords. Arneborg (2004) found that higher frequencies are most important for intermediary water exchange in the Gullmar Fjord.

Longitudinal variations of intermediary currents in the fjord

The current direction changes over time between ingoing and outgoing. It also changes vertically and most of the time the current probably has a two-layer structure as can be seen in the simulations by Stigebrandt (1990). Multilayer structure appears to evolve when the forcing is weak. The transport into the fjord is always equal to the transport out of the fjord. Due to vertical stratification, intermediary circulation is usually restricted to levels above sill level. It is only when the inflowing water is so dense that it can replace the basin water that intermediary circulation contributes to currents below sill depth.

The mean speed in the mouth U_i due to intermediary circulation equals

$$U_i = 2Q_i/A_m \quad (12)$$

Here $A_m = B_m H_t$ is the vertical cross-sectional area of the mouth and mean intermediary transport Q_i is given by Equation 10. Maximum currents should be a factor 2–4 greater than U_i , an analysis of the density field outside the fjord may be necessary to estimate this factor that may be different for different coastal stretches.

Assuming that the period of vertical motions induced by the coastal density field is long compared to the travel time of internal waves from the mouth to the head of the fjord, it may be assumed that the amplitude of vertical motion is similar in the whole fjord. The transport at a certain distance from the mouth should then be proportional to the area of the fjord inside the location. Introduce a longitudinal coordinate in the fjord such that the head of the fjord is at $x = 0$ and the mouth of the fjord at $x = L$. At the distance x from the head of the fjord (along the major fjord axis) the transport should be given by the following equation

$$Q_i(x) = Q_i \cdot \frac{A(x)}{A_f} \quad (13)$$

Here $A(x)$ is the horizontal surface area of the fjord inside the horizontal coordinate x and $A_f = A(L)$.

Mean speed forced by intermediary circulation at the distance x from the head of the fjord then equals

$$U_i(x) = U_i \frac{A_m}{B(x)H_t} \cdot \frac{A(x)}{A_f} \quad (14)$$

Here $B(x) \cdot H_t$ is the vertical cross-sectional area of the fjord above sill depth at distance x from the head. This

formula does not accommodate for damping of intermediary circulation with increasing distance from the mouth as found by Arneborg (2004) for the Gullmar Fjord.

Barotropic tidally driven circulation

Mean speed U_t through the mouth caused by a surface tide equals

$$U_t = \frac{dh}{dt} \cdot \frac{A_f}{A_m} - \frac{Q_f}{A_m} \quad (15)$$

Here A_f is the horizontal surface area of the fjord, A_m the vertical cross-sectional area of the mouth, dh/dt the rate of mean sea level change in the fjord, and Q_f the rate of freshwater supply to the fjord.

Together with a simple model of barotropic flow through straits giving the speed as a function of the sea level difference between the basins on the two sides of the strait, Equation 15 can be used to study tidal choking, see Stigebrandt (1980a, 1980b) and Wickbom and Rydberg (1996). If the speed is greater than the speed of internal waves in the neighboring basins, tidal flow through the strait will generate tidal jets close to the strait and not internal tides in the neighboring basins, see Section “Generation of Internal Tides and Tidal Jets at Sills”. A thorough analysis of observations from Loch Etive by Inall et al. (2004) shows a more complex picture.

Longitudinal variations of barotropic currents in the fjord

The first mode tidal response is a standing wave with a wavelength four times the length of the fjord and with a node in the mouth.

If one starts from the momentary transport Q_t , it is relatively simple to describe how the barotropic current amplitude changes from the mouth to the head of the fjord, thus

$$U_t(x) = U_t \frac{A(x)}{A_f} \frac{A_m}{A_{\text{vert}}(x)} \quad (16)$$

Here again $A(x)$ is the horizontal surface area of the fjord between the head and the distance x from the head and $A_{\text{vert}}(x)$ is the vertical cross-sectional area of the fjord at the distance x from the head (the vertical cross-sectional area at the mouth equals $A_m = A_{\text{vert}}(L)$). The speed will have local maxima where the vertical cross-sectional area has local minima. The barotropic response to tidal forcing of fjords was reviewed in Stigebrandt (1980a).

Present-day numerical tidal models are capable of computing very realistic barotropic tides and tidal currents, e.g., Davies et al. (2011) who compare different types of models.

Estuarine circulation

Freshwater that is supplied to a fjord by runoff and precipitation accumulates at the sea surface. Wind mixing may entrain underlying seawater into the surface layer which then becomes brackish. The outflow of brackish surface water is forced by the higher pressure of the surface layer

in the fjord than outside the fjord. It was shown by Stommel and Farmer (1953) that the surface water will attain the speed of a stationary internal wave when flowing through a topographic constriction in the mouth. Assuming that the stratification can be described by two superposed layers, the speed and thickness of the upper layer are U_{1m} and H_{1m} , respectively, and the speed and thickness of the lower layer U_{2m} and H_{2m} , respectively. The flow in a topographically constricted mouth can then be described by the following equation derived by Stommel and Farmer:

$$\frac{U_{1m}^2}{g'H_{1m}} + \frac{U_{2m}^2}{g'H_{2m}} = 1 \quad (17)$$

Here g' is the reduced gravity which equals $g \cdot \Delta\rho/\rho$ where $\Delta\rho$ is the density difference between the layers. This equation gives the relationship between the rate of flow through the mouth and the vertical stratification in the fjord at the mouth.

Under stationary conditions conservation of volume requires

$$Q_1 = Q_f + Q_2 \quad (18)$$

Here $Q_{1(2)}$ is outflow (inflow) through the mouth and Q_f is the supply of freshwater.

Conservation of salt requires

$$Q_1 S_1 = Q_2 S_2 \quad (19)$$

Here $S_{1(2)}$ is the salinity of brackish water (seawater).

If the effect of temperature may be ignored, the density of the brackish water may be written as

$$\rho = \rho_f(1 + \beta S) \quad (20)$$

Here ρ_f is the density of freshwater, β the coefficient of salt contraction ($\approx 0.0008\%^{-1}$), and S salinity (‰).

Due to acceleration toward the mouth, the thickness of the upper layer is greater in the (wider) fjord H_1 than in the (narrower) mouth H_{1m} , thus

$$H_1 = \phi H_{1m} \quad (21)$$

The coefficient ϕ is the ratio between the thicknesses of the surface layer in the fjord and in the mouth. Observations in fjords give ϕ -values in the range 1.5–2.7, see Green et al. (2004).

The flow of seawater into the surface layer is due to entrainment w_e performed by the wind-driven turbulence in the surface layer. The total flow by entrainment equals the horizontal surface area of the fjord A_f times w_e , thus

$$Q_2 = w_e A_f \quad (22)$$

The rate of entrainment can be computed from the following equation:

$$w_e = \frac{m_0 u_*^3}{g'H_1} \quad (23)$$

Here the empirical constant $m_0 = 0.6$ (Stigebrandt, 1985) and H_1 is the thickness of the upper layer in the fjord and u_* the friction velocity that equals the square root of the kinematic wind stress. If one assumes that the lower layer is thick and moves with low velocity Equation 17 degenerates to $U_{1m}^2 = g'H_{1m}$. For this case the following analytical solution for the thickness H_1 and the salinity S_1 of the surface layer may be obtained (Stigebrandt, 1981a):

$$H_1 = \frac{N}{2Q_f M} + \varphi \left(\frac{Q_f^2}{MB_m^2} \right)^{\frac{1}{3}} \quad (24)$$

$$S_1 = \frac{S_2 N}{N + 2\varphi \left[Q_f^5 \left(\frac{M}{B_m} \right)^2 \right]^{\frac{1}{3}}} \quad (25)$$

Here A_f is the area of the fjord, B_m the width of the mouth, W mean wind speed, $M = g\beta S_2$ and $N = C_e W^3 A_f$ where $C_e = 2.5 \cdot 10^{-9}$ is an empirical constant that contains among others the drag coefficient for air flow above the sea surface.

The first term on the right-hand side of Equation 24 is the Monin-Obukhov length determined by the buoyancy flux ($=g\beta S_2 Q_f / A_f$) and wind mixing ($\sim W^3$). The second term is the freshwater thickness, H_{1f} , determined by the hydraulic control. Using long series of observations of hydrographical profiles and freshwater supply, Green et al. (2004) showed that $H_{1f} \sim Q_f^{2/3}$ in Holandsfjord, Norway as predicted by the theory above. They also showed the power P spent on mixing (diapycnal buoyancy fluxes) is about 0.5 mW m^{-2} . If the efficiency of turbulence with respect to buoyancy fluxes R_f equals 0.06 (see Section Vertical Mixing in Fjord Basins below), the mean supply of power P/R_f is about $6\text{--}7 \text{ mW m}^{-2}$ from the wind to the surface layer. For comparison, Gustafsson and Stigebrandt (1996) estimated the mean wind power supply to Skagerrak to be about 36 mW m^{-2} . This difference might be reasonable because Holandsfjord is sheltered by very high mountains surrounding the fjord.

The model presented here should be valid for fjords with mouths narrower than the internal or baroclinic Rossby radius, i.e., $B_m < R_{oi}$ where $R_{oi} = c_i/f$. Here c_i is the speed of the internal wave in the stratification under consideration and f is the Coriolis parameter. The present author applied the fjord model to the Arctic Ocean that has mouths wider than R_{oi} (Stigebrandt, 1981b). The flow control equation, Equation 17 was replaced by the following equation relating geostrophic baroclinic transport to upstream stratification in a system with a deep lower layer, thus

$$Q_1 = \frac{g'H_1^2}{2f} \quad (26)$$

The freshwater content of the surface layer in Kattegat has been shown to be governed by a rotating hydraulic

control as expressed by Equation 26, see Stigebrandt and Gustafsson (2003).

Velocities caused by estuarine circulation

When the freshwater supply and the salinity of the brackish surface layer is known, one may compute the transport in the two layers

$$Q_1 = \frac{Q_f S_2}{S_2 - S_1} \quad (27)$$

$$Q_2 = \frac{Q_f S_1}{S_2 - S_1} \quad (28)$$

The speed U_e of the estuarine circulation inside the mouth can be estimated from the following expression:

$$U_e(x) = \frac{Q_1(x)}{B(x)H_1} \quad (29)$$

The transport $Q_1(x)$ varies with the distance from the source. There may be several sources at different longitudinal coordinates x and there may be different rates of initial mixing between freshwater and seawater in the mouths of the sources. The speed of the so-called compensation current in the lower layer is usually assumed to be weaker because it is assumed to be thicker. This is discussed by Stigebrandt and Molvaer (1996) who question if this is true for fjords with strong stratification beneath the surface layer.

Generation of internal tides and tidal jets at sills

Tides may supply huge amounts of energy to internal waves and jets that may feed turbulence and diapycnal mixing processes in fjords and, in particular, in the basin water where both wind-driven and intermediary circulation normally have small amplitudes. Internal tides and jets are also important in fjords because they may give strong contributions to the current field close to sills.

In stratified systems, harmonic currents driven by astromonic tides may generate internal waves at sloping bottoms. Stigebrandt and Aure (1989) differentiated between wave basins and jet basins. Basins in which internal tides are generated at sills are called wave basins. In jet basins, the tidal speed at the sill is greater than the speed of internal waves in the neighboring basin and tidal jets are generated.

To compute the generation of internal tides at fjord sills, it is assumed that surface and internal tides together fulfill the condition of vanishing flow normal to the bottom, e.g., Stigebrandt (1976, 1980b); Stacey (1984). This gives the amplitude of the internal tide for specified sill geometry and barotropic tidal flow.

Fjords often have a pycnocline at sill depth because the densest water appearing outside and above the fjord sill will fill the basin below the sill level, cf. Section "Exchange of Basin Water" below. The vertical stratification is then well approximated by two

homogeneous layers with the interface at about the sill depth, see Figure 5 for definitions.

If there were no sill at $x = 0$, the barotropic tidal speed would be

$$u_b = \alpha \cos(\omega t) \quad (30)$$

The amplitude α of the speed is given by topographical factors of the fjord and mouth, the frequency ω , and the sea level amplitude a_f of the tide in the fjord, which for simplicity is assumed to be the same in all parts of the fjord, thus

$$\alpha = \omega a_f \frac{A_f}{B_m(H_t + H_b)} \quad (31)$$

The barotropic and baroclinic tides together satisfy the condition of vanishing horizontal speed at the vertical sill, thus

$$u_b + u_{2i} = 0 \quad (32)$$

This gives the following orbital speeds in the upper and lower layers:

$$u_{1i} = \alpha \frac{H_b}{H_t} \cos(kx \pm \omega t) \quad (33)$$

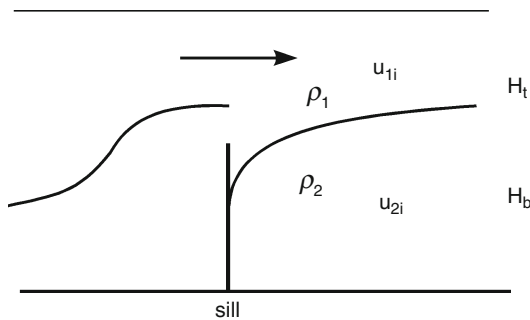
$$u_{2i} = -\alpha \cos(kx \pm \omega t) \quad (34)$$

The waves are progressive and move away from the sill along the x -axis. The wave number κ is defined by

$$\kappa = \frac{\omega}{c_i} \quad (35)$$

The speed c_i of an internal wave in two-layer stratification equals

$$c_i = \sqrt{g \frac{\Delta \rho}{\rho_0} \frac{H_t H_b}{H_t + H_b}} \quad (36)$$



Hydrodynamics and Circulation of Fjords, Figure 5 Definition of a two-layer system in a fjord with a vertical sill at $x = 0$. The water depth in the fjord is H and the sill depth is H_t and $H_b = H - H_t$. Internal waves are generated at the sill. The density is ρ_1 (ρ_2) and the orbital velocity is u_{1i} (u_{2i}) in the upper (lower) layer.

Here g is the acceleration of gravity and $\Delta \rho = \rho_2 - \rho_1$ and ρ_0 is a reference density. For wave generation it is required that $u_{1i} < c_i$ and $u_{2i} < c_i$. If these conditions are not fulfilled, the fjord should be a jet fjord. However, it seems that internal tides to some extent may be generated even in jet fjords by a decaying jet, see Section “Verification of the Model of Energy Transfer To Internal Tides” below.

Evidence shows that internal tides generated at fjord sills are progressive. The prominent internal tides at Dröbak sill in the Oslo Fjord, see Figure 6, are progressive and radiate away from both sides of the sill as shown using current and density observations from moored instruments (Stigebrandt 1979).

The orbital speeds u_{1i} , u_{2i} will be greatest close to the generating sill and decrease away from the sill because the waves may break and also because the basin usually becomes wider and deeper. One should expect that internal tides are radiating from all sills within fjords that generate internal waves.

Both the surface tide and internal tides may give important contributions to the current field in fjords. This should be particularly true in the basin water, beneath the sill level where the contributions from wind-driven and intermediary currents usually vanish.

The following densimetric Froude Number F_d can be used to theoretically differentiate between wave and jet basins:

$$F_d = \frac{\alpha}{c_i} \frac{H_b}{H_t} \quad (37)$$

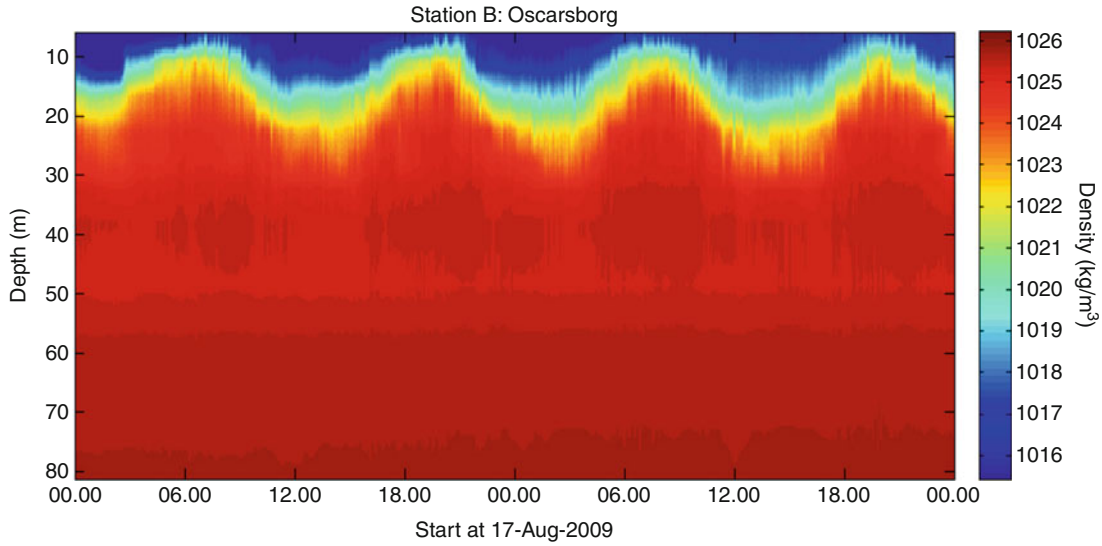
In laboratory experiments, it was found that internal waves were generated only if $F_d \leq 1$ (subcritical flow). For supercritical flow a jet or rotor developed at the lee side of the sill (Stigebrandt, 1976). If $H_b/H_t < 1$, i.e., for deep sills, the Froude number should be $F_d = \alpha/c_i$.

The model of generation of internal tides in a two-layer stratification presented above has been generalized to continuous stratification where instead a spectrum of internal waves satisfies the boundary condition together with the barotropic flow, e.g., Stigebrandt (1980b) who presented analytical solutions for the case of constant- N vertical stratification. Stacey (1984) and Sjöberg and Stigebrandt (1992) computed the baroclinic response at topography for arbitrary vertical stratification. Tverberg et al. (1991) used a numerical ocean model to study internal wave generation in fjords. They found strong response for internal waves in form of rays radiating out from sills. Several papers during the last years report studies of internal wave generation at sills using numerical ocean models, e.g., Berntsen et al. (2008).

Energy transfer to internal tides and jets at sills

The time-mean energy radiation from the generating sill by a progressive internal wave mode equals

$$P_T = B \cdot E \cdot c_{ig} \quad (38)$$



Hydrodynamics and Circulation of Fjords, Figure 6 Two days of observations inside the sill at Oscarsborg in the Oslo Fjord (sill depth ~ 18 m). The range of the semidiurnal surface tide is about 0.3 m while the range of the internal tide is about 10 m.

Here B is the width of the sill and c_{ig} the group velocity. The energy density E of a long internal wave of period T can be computed from

$$E = \frac{1}{T} \int_0^T \int_0^H \rho \cdot u_i^2 dz dt \quad (39)$$

Here $u_i(z)$ is the wave orbital speed and H the water depth in the adjacent basin. It has been assumed that the effect of Earth's rotations can be neglected in narrow fjords so that the contributions by potential and kinetic energy are equally large.

The mean energy flux into sill-generated long internal tides for two-layer stratification is (Stigebrandt, 1976)

$$P_T = B\omega^2 a_f^2 \frac{A_f}{2A_m} \frac{H - H_t}{H} c_{ig} \quad (40)$$

Here ω is the tidal frequency, a_f the sea level amplitude of the surface tide in the fjord, A_f (A_m) the horizontal area of the fjord (the vertical cross-sectional area of the sill section), H_t the sill depth, and H the mean depth of the fjord. The group velocity c_{ig} for long internal waves in two-layer stratification equals the phase velocity c_i given by Equation 36.

A jet develops on the lee side if the tidal flow over the sill is supercritical, $F_d > 1$, cf. Equation 37. The mean transfer of tidal power to a tidal jet flowing into the fjord equals (Stigebrandt and Aure, 1989)

$$P_{Tj} = 0.42\rho_0 u_0^3 \frac{A_m}{4} \quad (41)$$

Here u_0 is defined by

$$u_0 = a_f \omega \frac{A_f}{A_m} \quad (42)$$

The mean tidal power transferred to a jet flowing out of the fjord is equally large but it dissipates outside the fjord and cannot contribute to mixing in the fjord. Equation 41 accounts for this.

The tidal jet is primarily a barotropic phenomenon, caused by the large-scale topographic resistance formed by the sill section. However, the jet may induce various baroclinic phenomena like hydraulic jumps and high-frequency internal waves, e.g., Farmer and Freeland (1983). In the specific downstream vertical cross section where the speed of the jet has been reduced to the speed of the fundamental internal wave mode, the jet may excite an internal tide as observed in Sechart Inlet (Tinis, 1995; Tinis and Pond, 2001) and in Loch Etive (Inall et al. 2004). Some of the jet energy may in this way be transmitted to the basin water, see also Section “Vertical Mixing in Fjord Basins.”

Supported by qualitative observations of a laboratory experiment of generation of internal tides in a two-layer stratification, it was suggested that most of the energy in internal tides dissipate in the lower layer (Stigebrandt, 1976). In the following, it is assumed that this is true. Some estimates of normalized tidal energy supply to the basin water of fjords are presented in Table 1. It can be seen that the energy supply varies by three orders of magnitude. Some fjord basins receive more energy per unit horizontal surface area than does the abyssal ocean. Fjords are generally one or two orders of magnitude shallower than the ocean. In the basin water of highly energetic

fjords, the mean intensity of tidally forced turbulence may therefore be several orders of magnitude greater than the mean for the abyssal ocean, see also Section “[Vertical Mixing in Fjord Basins](#).”

For comparison it might be interesting to know the energy supply by winds. In [Table 2](#) it can be seen that the power supply by winds to deeper water layers is generally smaller than the supply by tides. However, the energy supply by wind to the surface layer in Holandsfjord was estimated to 6–7 (mW m^{-2}), see Section “[Estuarine Circulation](#).” A comparison with the supply to deeper layers in [Table 2](#) suggests that most wind energy is dissipated in the surface layers and only a small fraction is transmitted to lower layers.

Verification of the model of energy transfer to internal tides

The model of barotropic to baroclinic energy transfer at sills has been verified using several independent methods, see [Figure 7](#) for an overview of methods. The tidal phase lag ϕ across sills caused by the resistance to barotropic tidal flow induced by baroclinic wave drag can be computed (method 1), and theoretical estimates have been

verified for several fjords, e.g., Stigebrandt (1999). The predicted damping of barotropic seiches due to baroclinic wave drag at sills (method 2) has been verified for the Gullmar Fjord (Parsmar and Stigebrandt, 1997). The predicted rates of buoyancy fluxes due to vertical mixing driven by internal tides (method 3) have been verified for many fjords, see Section “[Vertical Mixing in Fjord Basins](#)” below. The intuitively most obvious method to verify models of baroclinic wave drag is to compare computed and observed internal tide radiation away from a sill (method 4). However, this method is difficult to apply in many fjords because internal tides often lose much of their power already close to the sills where they are generated, cf. deYoung and Pond (1989); Stigebrandt (1999); and Arneborg et al. (2004a).

The process of energy transfer from other motions to baroclinic waves may also give rise to flow resistance or drag and may therefore be denoted baroclinic wave drag, see Stigebrandt (1999) for examples of flow resistance.

Vertical mixing in fjord basins

Observations in fix points show turbulence as high-frequency fluctuations of velocity, salinity, temperature, and other state variables. The vertical flux of, for instance, sea salt may be estimated as the time average of the product of the fluctuating components of the vertical velocity w' and the salinity S' , respectively. It is common to describe the turbulent vertical flux of a scalar as a product of the vertical turbulent or eddy diffusivity κ and the vertical gradient of the scalar. For a given locality, it is reasonable to assume that the same value of κ may be used to compute vertical turbulent transports of different scalars. Thus, for vertical fluxes of salt S and temperature T one obtains

$$\kappa \cdot \frac{\partial S}{\partial z} = \overline{w'S'} \quad (43)$$

$$\kappa \cdot \frac{\partial T}{\partial z} = \overline{w'T'} \quad (44)$$

Here z is the vertical coordinate, increasing upward. Similar expressions can be formulated for vertical fluxes of other scalars.

Hydrodynamics and Circulation of Fjords, Table 1 Some published estimates of the energy transfer from tides to internal tides and tidal jets fjords. The figures are normalized by the horizontal surface area A_t of the fjords at sill depth. For comparison, estimates of the mean energy transfer to internal tides in the deep ocean (below 1,000 m depth) are also shown

Fjord, name	P_T/A_t (mW m^{-2})	Reference
Oslo Fjord (Vest Fjord)	7	Stigebrandt (1976)
20 Norwegian wave fjords	0.8–5	Stigebrandt and Aure (1989)
Gullmar Fjord	0.5	Arneborg and Liljebladh (2001b)
Ringdals Fjord	25	Johnsson et al. (2007)
The Ocean (below 1,000 m)	3 4	Egbert and Ray (2001) Sjöberg and Stigebrandt (1992)
9 Norwegian jet fjords	2–142	Stigebrandt and Aure (1989)

Hydrodynamics and Circulation of Fjords, Table 2 Some published estimates of the energy transfer P_W from winds to the layers beneath the surface layer. The figures are normalized by the horizontal surface area A_t of the fjords at sill depth except for the Baltic where the surface area at the depth of the halocline (70 m) has been chosen

Fjord, name	P_W/A_t (mW m^{-2})	Reference
Gullmar Fjord (surface + internal seiche)	0.5 ($R_f = 0.06$)	Arneborg and Liljebladh (2001b) (see comment at the end of Section “ Wind Drift and Related Phenomena ”)
Norwegian fjords	0.3 ($R_f = 0.06$)	Stigebrandt and Aure (1989)
Lake Alpnach (weak winds, about 3 ms^{-1})	0.12	Wüest et al. (2000)
Baltic proper (required to explain the observed vertical mixing of the deepwater)	1 ($R_f = 0.08$)	Axell (1998)

An equation for the turbulent flux of density $\overline{w'\rho'}$ may be obtained using the equation of state for seawater:

$$\rho = \rho_0(1 - \alpha T + \beta S) \quad (45)$$

where ρ is density, α the coefficient of heat expansion, and β the coefficient of salt contraction. If Equations 43 and Equations 44 are multiplied by $\rho_0\beta$ and $\rho_0\alpha$, respectively, and the latter resulting product is subtracted from the former and using the equation of state, the following equation may be obtained:

$$\kappa \cdot \frac{\partial \rho}{\partial z} = \overline{w'\rho'} \quad (46)$$

Buoyancy is denoted by $g' = g\rho'/\rho_0$, where g is the acceleration of gravity, ρ' the fluctuating part of the density, and ρ_0 a reference density. The buoyancy flux $b = \overline{w'g'}$ is obtained if Equation 46 is multiplied by g/ρ_0 , thus

$$\overline{w'g'} = \kappa \cdot N^2 \quad (47)$$

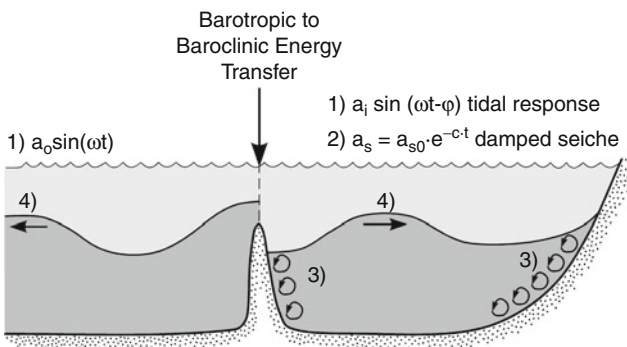
Here $N^2 = -g/\rho_0(\partial\rho/\partial z)$ is the buoyancy frequency. The buoyancy flux b expresses the rate of work against the buoyancy forces (per unit mass, i.e., Watt kg^{-1}) performed by mixing processes in stratified fluids.

In a closed volume containing stratified fluid, turbulent energy cannot escape, neither by radiation of gravity waves nor by advection and diffusion. Only a fraction of the available turbulent power p is used for work b against the buoyancy forces while the remainder ε dissipates to heat by molecular friction, thus

$$b + \varepsilon = p \quad (48)$$

It is often assumed that b is a fixed fraction R_f of p , thus $b = R_f \cdot p$. The so-called flux Richardson number, R_f , is the efficiency of turbulence with respect to execution of buoyancy fluxes. Using $\varepsilon = (1 - R_f)p$ and Equation 47, the buoyancy flux can be expressed in terms of R_f and ε as

$$\kappa \cdot N^2 = \frac{R_f}{1 - R_f} \cdot \varepsilon \quad (49)$$



Hydrodynamics and Circulation of Fjords, Figure 7 Four different methods to verify the model of energy transfer to internal tides at fjord sills are indicated in the figure.

This equation can be used to estimate κ if the dissipation ε can be estimated from observations of so-called micro-structure and R_f is known. The numerical value of the efficiency factor R_f is discussed below.

Power from tides P_T and winds P_W sustains the turbulence in the basin water of fjords. In analogy with Equation 48, it may be assumed that some of the power is used for buoyancy fluxes P_B while the remainder dissipates to heat P_D , thus $P_B + P_D = P_T + P_W$. The power P_B used for buoyancy fluxes is assumed a fixed fraction R_f of the power supply, thus

$$P_B = R_f(P_T + P_W) \quad (50)$$

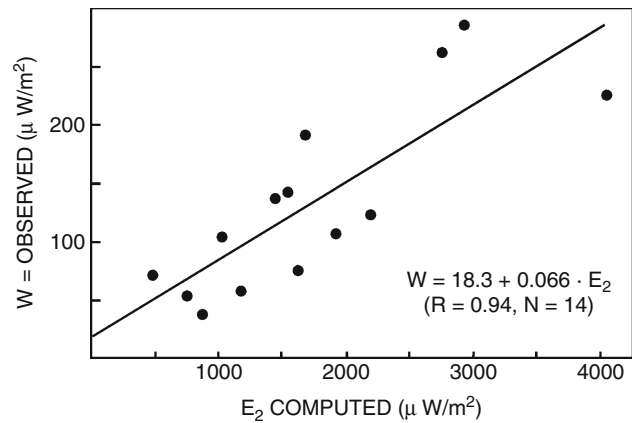
This equation may be regarded as a definition of the overall (or system or bulk) flux Richardson number R_f .

The total rate of work against the buoyancy forces, P_B , by mixing processes in the basin water of a fjord is obtained by integration of the buoyancy flux, from greatest depth $z = d$ to the sill level $z = h$, thus

$$P_B = \int_b^h \rho_0 \kappa(z) N(z)^2 A(z) dz \quad (51)$$

Thus, P_B can be computed from Equation 51 if the horizontal mean diffusivity $\kappa(z)$ has been estimated for a fjord basin using the budget method described in Section “Stratification Changes in Small Fjords Due to Water Exchange and Mixing.”

Several authors have published estimates of the rate of work against the buoyancy forces using Equation 51. In Figure 8, the observed work against the buoyancy forces, $W = P_B/A_t$ has been plotted against the energy transfer by internal tides to the basin water $E_2 = P_T/A_t$. Comparing the regression line as written down in Figure 8 with



Hydrodynamics and Circulation of Fjords, Figure 8 Observed buoyancy fluxes versus theoretically estimated energy flux to internal tides in fjord basins in Møre and Romsdal (From Stigebrandt and Aure, 1989).

Equation 50 shows that the slope of the line equals the flux Richardson number, thus $Rf \approx 0.066$, and the interception of the fitted line with the vertical axis is RfP_W . This gives $P_W \approx 0.3 \text{ mWm}^{-2}$, see also Table 2. Figure 8 shows that there is a very good correlation between observed buoyancy fluxes and theoretical power supply to turbulence in the basin water. The flux Richardson number estimated here is the bulk flux Richardson number. Similar values of the bulk flux Richardson number has been estimated for many fjord basins, starting with Stigebrandt (1976) who estimated $Rf = 0.05$ for the Oslo Fjord. The rigorous analysis of the Gullmar Fjord by Arneborg and Liljebladh (2001b) gave $Rf = 0.07$.

For jet fjords, Stigebrandt and Aure (1989) found that $Rf = P_{Tj}/A_t$ is only about 0.01. They suggested that this is because the jets are dissipated essentially above the sill basins and only a smaller fraction of the jet energy P_{Tj} is transmitted to the basin water, cf. Tinis and Pond (2001) and Inall et al. (2004).

The bulk flux Richardson number as determined from observed buoyancy fluxes in fjord basins and estimates of the energy supply from tides are typically in the range 0.06–0.07 for wave basins which is less than half of the value 0.2 often used in oceanography. However, Arneborg (2002) has explained why the patch flux Richardson number is about twice the overall flux Richardson number.

Coupling vertical mixing and energy supply to turbulence

Based on some seasonally averaged diffusivities in lakes and fjords, Gargett (1984) suggested that the diffusivity in the deepwater of the Ocean should be proportional to N^{-1} , thus

$$\kappa = \alpha_0 \cdot N(z)^{-1} \quad (52)$$

Here α_0 is an empirical intensity factor (velocity squared) accounting for the mean mixing activity of turbulence. Using the relationship given in Equation 49 between κ and ε and assuming $Rf = 0.2$, Gargett (1984) estimated $\alpha_0 = 1 \cdot 10^{-7} \text{ m}^2 \text{ s}^{-2}$ from available estimates of dissipation ε from the open ocean.

Starting from the parameterization of κ in Equation 52 and using Equation 51 as an integral condition, one may develop the following parameterization of the horizontal and time mean $\kappa(z)$ as function of forcing $P_T + P_W$ and stratification $N(z)$, thus

$$\kappa = \frac{W}{\rho_0 H_b M} N^{-1} \quad (53)$$

Here $W = P_B/A_t = Rf(P_T + P_W)/A_t$ is the power used for buoyancy fluxes by mixing in a vertical column of a basin with upper horizontal surface area A_t , H_b is the mean thickness of the deepwater layer, and M the area weighted vertical mean of N in the basin water of volume V_b defined by

$$M = \frac{1}{V_b} \int_d^h N(z) A(z) dz \quad (54)$$

A slightly more detailed parameterization was developed by Stigebrandt and Aure (1989). This included a fjord-specific constant depending on both stratification and topography.

The parameterization by Stigebrandt and Aure (1989) is probably the first example in oceanography of a relationship between the vertical diffusivity in a stratified water column and the theoretically estimated external forcing W of the turbulence. This equation implies that the vertical diffusivity can be predicted in fjords as long as the forcing can be estimated from tidal amplitude, stratification, and topography. Simple methods to estimate P_T are described in Section “Generation of Internal Tides and Tidal Jets at Sills.” However, in fjords with weak tides, like the Gullmar Fjord (see Tables 1 and Tables 2), the wind contribution P_W may be important (Arneborg and Liljebladh, 2001b).

Observations of mixing in fjords

The budget method has been applied to numerous fjord basins to estimate the vertical diffusivity. Gade (1970) obtained for the Vestfjord values in the interval $0.07 < \kappa < 20 \text{ (cm}^2 \text{ s}^{-1})$ and for Bunnefjord generally lower values. Svensson (1980) used both sea salt and a basin-wide cloud of Rhodamine B in the Byfjord, Sweden and got values in the interval $0.005 < \kappa < 0.06 \text{ (cm}^2 \text{ s}^{-1})$. Smethie (1980) used salt and radon-222 (forming at the decay of radium-226 stored in the sediment) as tracers in a number of Canadian fjords and got values in the interval $0.08 < \kappa < 9 \text{ (cm}^2 \text{ s}^{-1})$. Stigebrandt and Aure (1989) estimated the vertical diffusivity in about 30 Norwegian fjord basins. Values as low as about twice the molecular diffusivity of salt were obtained in Framvaren, a deep and almost tied off and tide-less fjord near the southwestern tip of Norway (Frøyland, 1966).

A cloud of Rhodamin B was released in the basin water of inner Oslo Fjord (Bjerkeng et al., 1978). In the initial phase, the horizontal area of the tracer cloud was small compared to the area of the fjord and the cloud had no contact with the bottom boundary. During this phase, the vertical diffusivity, as computed from the evolution of the tracer cloud, was an order of magnitude less than the vertical diffusivity as estimated from the budget method applied to salt. In Stigebrandt (1979), this observation was taken as evidence for dominance of boundary mixing as anticipated already in Stigebrandt (1976). Similar results were obtained in an Arctic fjord where short-term measurements of vertical diffusion of a radioactive tracer injected at different depths gave about ten times smaller diffusivity than salt-derived values (Lewis and Perkin, 1982). A tracer experiment in Loch Etive showed the dispersion structure of boundary mixing driven by breaking internal waves (Inall, 2009). From observations of

microstructure profiles, Inall and Rippeth (2002) found that the vertical eddy diffusivity is about $0.5 \text{ (cm}^2\text{s}^{-1}\text{)}$ in the deepwater of the Clyde Sea. This is about half of the horizontal and time mean value expected from the budget method. The authors concluded that the mixing missing in their observations should occur near the entrance sill and/or at the sloping boundaries of the deep basin. This conclusion is supported by recent microstructure measurements in the Gullmar Fjord by Arneborg et al. (2004a).

It thus seems that most of the vertical mixing in the basin water of fjords is executed close to the bottom boundary. This seems to be the case also in lakes. Tracer experiments were done in the 1990s in Lake Alpnach (central Switzerland). Like the tracer experiment in the Oslo Fjord and other fjords, these experiments showed that most (about 90%) of the vertical mixing is executed close to the bottom boundary (Goudsmit et al., 1997).

Exchange of basin water

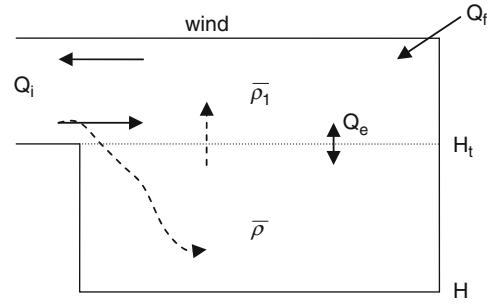
The residence time T_e of the basin water below sill level may depend on the following three factors: the spectral distribution of the temporal density variability of the coastal water, the rate of diapycnal mixing of the basin water, and the time T_{fill} it takes to fill the basin with new deepwater. The latter is determined by the transport capacity of the mouth and the volume of the basin water. The two-layer transport capacity of a strait was investigated by Stommel and Farmer (1953), see Section “[Estuarine Circulation](#)” above. The present author investigated how barotropic fluctuations could increase the transport capacity of a strait with respect to exchange of two water masses (Stigebrandt, 1977). Farmer and Armi (1986) investigated the control of two-layer transport through horizontal and vertical constrictions in the presence of barotropic fluctuations.

A model calculating T_e and the mean density of the basin water was developed by Stigebrandt and Erlandsson (2006). In the model, see [Figure 9](#), the water exchange is driven by horizontal density differences between the fjord and the offshore area above sill level, i.e., by intermediary circulation as described in Section “[A Simple Empirical Model of Intermediary Circulation](#).” The residence time of the basin water is divided in periods of filling and stagnation in the basin water and the lengths of those periods was identified from the model results. The model requires that the variability of the offshore density field, ρ_{in} , is resolved in spectral bands and that the rate of vertical mixing in the basin water is known.

The rate of mean density reduction in the basin water due to diapycnal mixing can be written as (Aure and Stigebrandt, 1990):

$$\frac{d\bar{\rho}}{dt} = -\frac{C_W W}{gH_b^2} \quad (55)$$

Here $W = P_B/At$ where is defined by [Equation 51](#) and At is the horizontal surface area of the fjord at sill level, C_W is an empirical nondimensional constant (≈ 2), g the



Hydrodynamics and Circulation of Fjords, Figure 9 Vertical cross section through a fjord describing the physical transports during stagnant periods of the basin water (*solid lines*) and during basin water renewals (*dashed lines*). Q_f is the freshwater input, Q_i is the intermediary exchange between the coastal water and the fjord, and Q_e is the turbulent exchange flow between the basin water and the water above sill depth.

acceleration of gravity and H_b the mean thickness of the basin water. For model computations, Stigebrandt and Erlandsson (2006) described the effect of diapycnal mixing as a two-way exchange Q_e that they derived from [Equations 51](#) and [Equations 55](#), thus

$$Q_e = \frac{2Rf(P_T + P_W)}{g(\bar{\rho} - \bar{\rho}_1)H_b} \quad (56)$$

To keep the model as simple as possible, density is considered to be a function of only salinity, and the equation of state in [Equation 20](#) is used. In addition, the freshwater supply is turned off, i.e., $Q_f = 0$. The response of the spatial mean salinity S of the basin water, of volume V_b , to inflow of new deepwater of salinity S_{in} and to vertical mixing with the upper layer of salinity S_1 is described by the following equation:

$$\frac{dS}{dt} = \varepsilon \frac{Q_{\text{in}}}{V_b} (S_{\text{in}} - S) + \varepsilon_1 \frac{Q_e}{V_b} (S_1 - S) \quad (57)$$

For the model computations, Q_{in} is due to intermediary circulation according to [Equation 10](#).

The spatial mean salinity S_1 of the upper layer is described by the following equation:

$$\begin{aligned} \frac{dS_1}{dt} = & (1 - \varepsilon) \frac{Q_{\text{in}}}{V_1} (S_{\text{in}} - S_1) + \varepsilon_1 \frac{Q_e}{V_1} (S - S_1) \\ & + \varepsilon \frac{Q_{\text{in}}}{V_1} (S - S_1) \end{aligned}$$

Here the volume of the upper (lower) layer is V_1 (V_b). The switch functions ε and ε_1 are defined as follows; ε equals 1 if $S_{\text{in}} > S$ and 0 otherwise; ε_1 equals 1 if $S_1 < S$ and 0 otherwise.

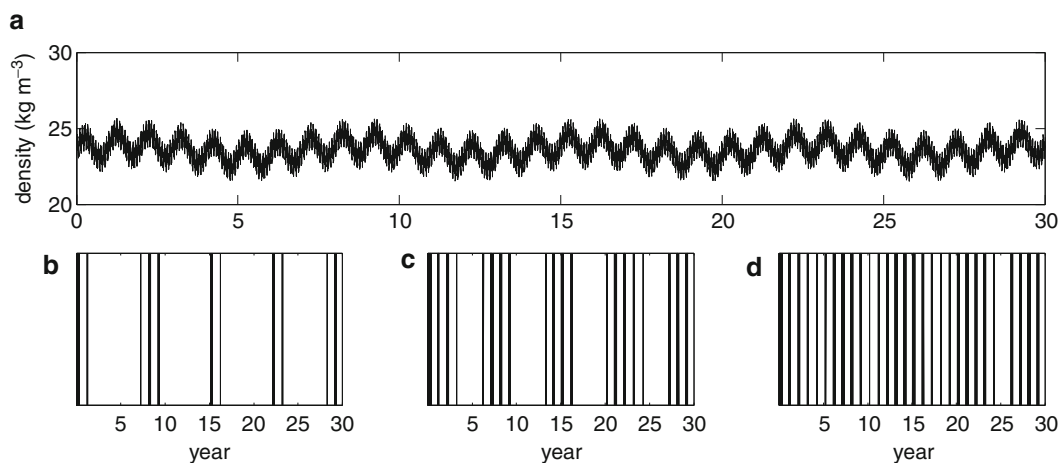
The model was run for two cases with different forcing of the intermediary flow. The variability of ρ_{in} was partitioned into periods of 1 week, 1 month, 1 year, and 7 years. In Case 1, the percentage contributions to the

variability from the different period bands were (18,18,52,12) and in Case 2 the long-term component was turned off and the variability was described by (22,22,56,0). The total variability was the same in the two cases.

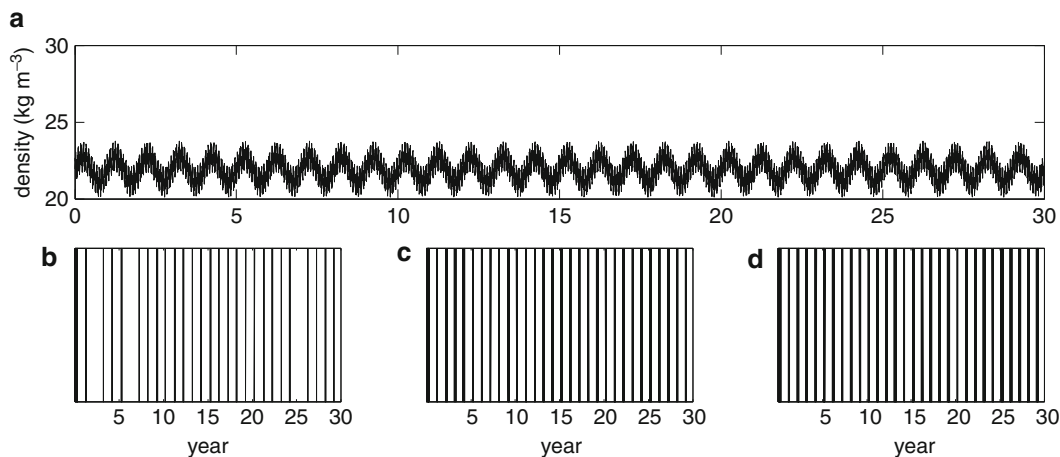
Figure 10 shows that the fjord with the weakest mixing is stagnant for several years in Case 1. This is due to combination of weak mixing rate and appreciable variation of the external density field on the timescale of several years. If the mixing rate increases, the length of the stagnation periods decreases, cf. case (c) and (d) in Figure 10. If the long-term variability is turned off (Case 2), the frequency of water exchange increases drastically, in the fjord with the weakest mixing, Figure 11. However, there are still

some years that lack water exchange due to the variability induced by higher frequencies.

From their model runs Stigebrandt and Erlandsson (2006) identified two different classes of systems. *Mixing systems* have short T_{fill} and T_e depends on the rate of diapycnal mixing in the basin water and on the spectral distribution of the density variability in the coastal water. Long-period variations in the offshore density field (e.g., the North Atlantic Oscillation with a period of several years) may determine T_e if the mixing in the basin water is weak. *Transport systems* have long T_{fill} and T_e is determined by the baroclinic transport capacity of the mouth. Such systems are “over mixed,” which means that increasing the rate of vertical mixing of the basin water will have



Hydrodynamics and Circulation of Fjords, Figure 10 Results of a 30-year-long simulation for Case 1. (a) The top panel shows the variations of density at sill level in the coastal water. The three panels (b–d) show periods of stagnation (white) and periods of exchange (black) of the basin water for three different values of mixing rates (dp/dt) (-0.0001 , 0.0005 , -0.0010) ($\text{kg m}^{-3} \text{ day}^{-1}$) with increasing rates from left to right.



Hydrodynamics and Circulation of Fjords, Figure 11 The same conditions as described in Figure 10 except for the water exchange with the sea which is according to Case 2.

no effect on T_e , cf. Stommel and Farmer (1953). If the locally supplied freshwater is turned off, i.e., $Q_F = 0$, the temporal and spatial mean density of the basin water was shown to equal the offshore temporal mean density at sill level and T_e equals two times T_{fill} in that case. The Baltic proper is a good example of a transport system with strong barotropic currents usually overriding the baroclinic currents in the mouth.

In the model described above, new basin water is not mixed with the old basin water which it is in real systems. New basin water flows along the bottom as a dense bottom current which entrains old basin water on its way to greater depths. Thereby the new deepwater will be a mixture of the old basin water and the new water flowing across the mouth. A simple model of an entraining dense bottom current was described in Stigebrandt (1987). Entrainment into dense bottom currents in fjords has been described by Liungman et al. (2001) and Arneborg et al. (2004b). The dynamics of entraining dense bottom currents was studied experimentally and theoretically by Umlauf and Arneborg (2009a, 2009b).

Wind drift and related phenomena

The relative effects of wind, tide, and river runoff on the circulation of the surface layer of a small fjord were investigated by Buckley and Pond (1976) using drogues that were tracked with radar for several days. They found that wind forcing was dominant. River runoff was also important since it caused large horizontal shears in the flow. Tidal effects were negligible. Due to a strong pycnocline, the surface layer appeared to be nearly decoupled from the underlying water. This is in line with the concept slippery sea due to almost laminar flow conditions between the surface layer and the underlying water (Houghton and Woods, 1969). Stacey (1999) demonstrated that a numerical model could simulate the near surface wind-forced currents in Knight Inlet quite well.

Fluctuating winds along the axis of a fjord may generate both surface and internal seiches (standing long waves). Well developed fundamental mode surface seiches occur in the Gullmar Fjord. The seiches occur also when the fjord is covered by land-fast ice which shows that they can be generated remotely by rapid changes of the pressure field outside the mouth of the fjord, e.g., Parsmar and Stigebrandt (1997). These authors showed that the surface seiche in the Gullmar Fjord is dampened by the generation of internal waves at the sill with the same frequency as the seiche by the mechanism described in Section “[Generation of Internal Tides and Tidal Jets at Sills](#).” These internal waves contribute about 25% of the energy for turbulence and mixing in the basin water of the fjord. Gullmar Fjord also has large internal seiches generated by both local wind and waves in the coastal stratification see Arneborg and Liljebladh (2001a). In a companion paper they show that internal seiches contribute about 35% and internal tides about 40% of the energy available for turbulence and mixing in the basin water (Arneborg and Liljebladh, 2001b). However, since variability in the

coastal water (Section [Intermediary Circulation Forced by Density Variations in the Coastal Water](#)) apparently contributes to generation of both surface and internal seiches, it might be fair to estimate that the local wind contributes 30%, the variability of the coastal density field 30% and tides 40% of the energy available for turbulence in the basin water of Gullmar Fjord.

Hydrodynamics of fjords applied to fish farming

In many practical applications, it is important to know the current conditions in a certain location of a fjord. One example is aquaculture where it is necessary to estimate the carrying capacity which is the largest possible biomass of the cultured species that can be grown in a certain location without unacceptable effects on the environment and on the farmed stock. The carrying capacity may be estimated from several simultaneously valid criteria, all giving different estimates. The lowest of these then defines the carrying capacity, see e.g., Stigebrandt (2011) and Tett et al. (2011) for overviews and models.

For fish farming in cages, the current flushing the cages is very important since it brings oxygen to the fish and at the same time removes dissolved wastes produced by the fish. Since the fish might be seriously hurt if the oxygen concentration in the cages becomes lower than a certain value (different for different species), it is of utmost importance to know the minimum flushing rate of the cages which occurs in periods of minimum current speed. Particulate waste, i.e., feces and non-eaten feed, sink through the bottom of the cages. Before reaching the sea bed it will be dispersed by time-varying currents. Current variability is thus an important factor in determining the specific loading of the bottom with organic matter. Organic matter that reaches the seabed will feed benthic animals. However, if the oxygen demand to decompose the organic matter that reaches the sea bed is greater than the supply of oxygen, anoxic conditions may develop below the fish farm meaning that animals may not live there and the organic waste from the farm will be decomposed by anaerobic processes producing hydrogen sulfide and methane. It is thus necessary to know the minimum transport of oxygen to the bottom in order to estimate the largest flux of organic matter that allows living benthic animals beneath the farm in periods of weak currents. The current properties described here are necessary to know to compute the carrying capacity of a certain farmed species at a certain location. There may be other current properties, connected to the horizontal spreading of infectious diseases and sea lice between farms, that also are important to know before farms are established. Of course, there may be other human needs to know additional current conditions in fjords, not mentioned in this entry.

Summary

Fjords provide excellent environments for studies of several hydrodynamic processes. The upper layers of many

fjords have baroclinic estuarine circulation, internally driven by local freshwater supply and wind mixing. The amount of freshwater in the surface layer may be hydraulically controlled by the topography of the mouth. Topography is also important for tidal circulation and for generation of internal tides and jets and topography may isolate basins by preventing water exchange with neighboring basins and with the coastal area. Exchange of water in isolated basins, below sills, is driven by diapycnal mixing that decreases the density. Turbulence in sill basins usually gets most of its power from tides via internal tides and jets. Externally forced baroclinic circulation, driven by temporal variations of the vertical density distribution in the coastal water outside fjords, is usually much larger than the internally forced estuarine circulation. The understanding of important hydrodynamic fjord processes and internally and externally forced circulation modes of fjords and isolated deep fjord basins is reviewed using observations and simple dynamical models. It is finally shown that knowledge of many properties of fjord circulation is necessary to determine the carrying capacity of localities in fjords for fish farming.

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Cross-references

[Circulation Processes in Lakes](#)
[Coastal Lagoons](#)
[Estuarine Hydrology](#)
[Laurentian Great Lakes, Interaction of Coastal and Offshore Waters](#)
[Thermal Bar](#)
[Thermal Regime of Lakes](#)
[Thermobaric Stratification of Very Deep Lakes](#)

HYDRODYNAMICS OF VERY SHALLOW LAKES

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Introduction

Very shallow lakes, being shallow all over, are special compared to lakes that are deep at some places in that they are so much influenced by bottom processes and near-shore processes. These lakes are only few meters deep and are well mixed in the vertical. Only during daytime the surface water temperature may slightly differ from the bottom water temperature. Wind-induced waves cause bottom material from almost the entire lake bottom to resuspend during strong winds. Vegetation progresses from the shores into the lake and there may be patches with reeds or submerged vegetation also in the middle of such a lake. A small lake level drop results in rather large decrease of the lake volume, which together with resuspension of bottom material may result in large increases of the concentration of different constituents. Resuspension brings nutrients from the sediments to the water, but also reduces the penetration of solar radiation.

The water in a very shallow lake is forced to move from direct wind impact, wind-induced circulation, from the

setup of the water surface and the consequent forth-back movement, when the wind ceases to blow, i.e., seiche currents, and from nonuniform heating of the water surface when the heat exchange is different within vegetation belts and on open water, which induces large-scale convective motions.

Wind-induced circulation

The currents in a shallow lake are primarily driven by the wind. However, there is no wind stress within the reed vegetation and there are sheltered areas behind the vegetation in the open lake. When the wind is strong, there is complete mixing from surface to bottom and the current is in the same direction over the whole depth. With no or little vegetation the circulation tends to be such that the currents are in the wind direction along the shores but against the wind in the middle of the lake, which is very different from deeper lakes, where the return current is at greater depth. The surface currents are of the order 1% of the wind speed or less, but the circulation is much affected by the distribution of the vegetation and can be quite complex with many gyres as is found from many Hungarian studies. Wind-driven currents have been extensively studied in Hungarian lakes from field observation, physical model studies, and mathematical models, e.g., Josza (2006). The return currents against the wind tend to be much within reed belts, where there is no direct stress from the wind on the water surface. Also nonuniform wind stress due to wind protection of the shores induces gyres and complex circulation pattern, e.g., Podsechine et al. (1999).

Seiche currents

The setup of the water surface is very minor, of the order mm/km in most lakes, but it is inversely related to the water depth, so it is more in shallow than deep lakes, see the entry [Circulation Processes in Lakes](#). The speed of the seiche moving back and forth along the lake is that of a gravity wave. When the water is moving back and forth there is exchange of water from the open water into nearshore reed belts. The process is, however, poorly quantified.

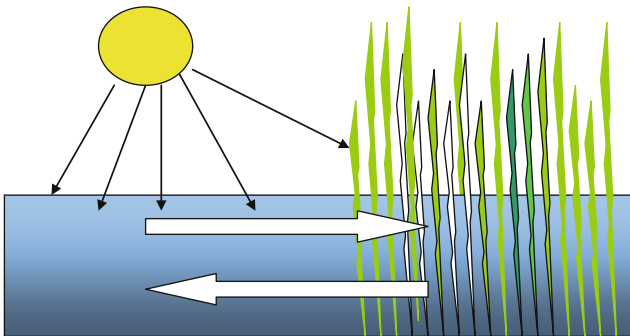
Water exchange between vegetation belts and open water

Differential heating of surface waters within vegetation belts and open water induces convective large-scale currents between the nearshore water and the open lake. In daytime the water within the vegetation is shaded from solar radiation and in nighttime the vegetation reduces the back radiation to the atmosphere. In daytime the water in the open lake tends to be warmer than the water within the vegetation, which results in a current system with surface water flowing into the vegetation and a compensating outward movement near the bottom, as is illustrated in [Figure 1](#). In nighttime the current system is the reverse. In Lake Kranke in the very south of Sweden up to 1°C

temperature difference has been observed and currents of 1.5 cm/s, Borell-Lövstedt and Bengtsson (2008a). Similar current systems due to differential heating develop between bays and open deeper waters in a lake, MacIntyre et al. (2002).

Waves

Waves in shallow lakes are small and short and reach full height already after short duration. It seems they can be well predicted with empirical fetch limited deep water wave forecasting equations developed for the ocean. The waves are damped, when passing through vegetation or



Hydrodynamics of Very Shallow Lakes, Figure 1 Water exchange between open water and vegetation belt during a sunny day.

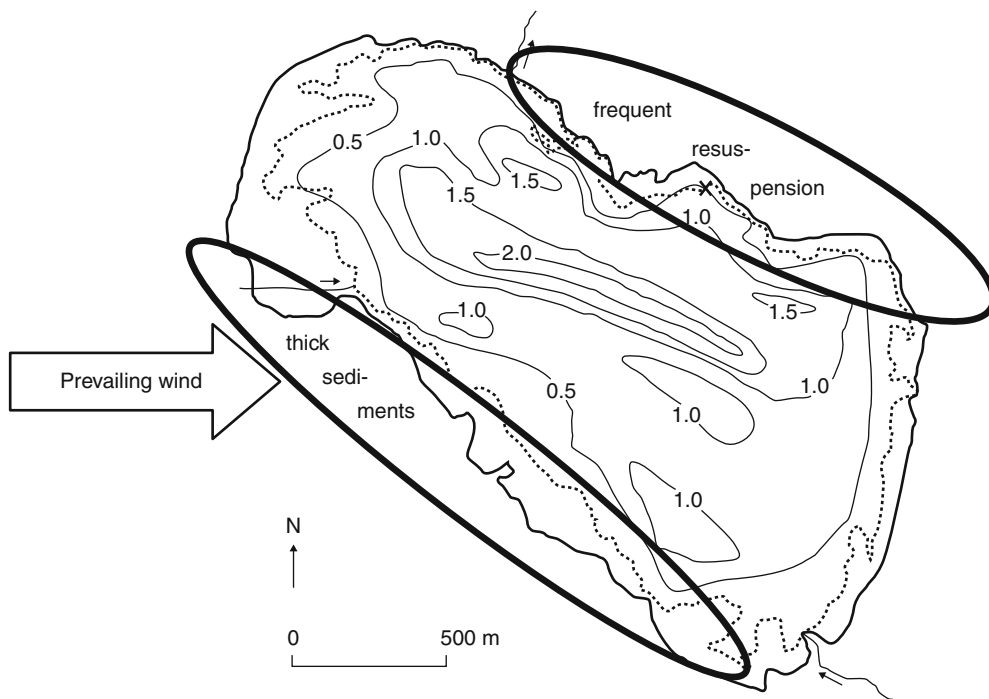
over submerged vegetation. In Lake Kranke the waves are damped about 50% after traveling through 10 m reed of density about 40 m^{-2} when the average stem diameter is about 4 mm. Studies on coastal sea grass show about the same or less damping with higher waves than those in a small lake. The wave height, H , downstream the vegetation can be determined (reduced from H_0 upstream the vegetation) by an equation like, see Borell-Lövstedt and Larson (2010),

$$H = H_0 / (1 + ND F C_d x)$$

where N is reed stem density, D is the stem diameter, C_d is drag coefficient, and where F is a function of wave characteristics (period, length, and height) and of water depth. It is seen that the damping effect as per meter is reduced through the reed belt along x . The effect of the concentration of reeds is large. Doubling ND means an approximate double reduction of the wave height over 10 m.

Resuspension

In a very shallow lake there are no accumulation bottoms. Material brought in suspension accumulates all over the lake and can be resuspended at every storm occasion. However, sediments within vegetation may accumulate until a severe storm comes from special directions. Since material is settled all over the lake bottom the sediments are not sorted. Erosion of bottoms may be due to inflowing rivers or large bottom currents, but are almost always caused by wind-induced wave action. Bottom material is



Hydrodynamics of Very Shallow Lakes, Figure 2 Accumulation and frequent resuspension bottoms in Lake Kranke.

eroded, when the shear at the bottom exceeds a threshold value. The erosion rate, E , is determined as

$$E = C_e(\tau/\tau_c - 1)$$

where C_e is a coefficient, which depends on the character of the sediments, τ is the bottom shear, and τ_c is the critical shear stress. However, the source of erodable material for a given shear stress is limited. After not very long storm duration all this material is brought in suspension. The amount of material brought in suspension is the net entrainment depth times the erodable lake bottom area. The entrainment, e , is related to τ/τ_c just as the erosion rate is. Lick (1982) suggested an exponent of $b = 2$ in the expression

$$e = C_n(\tau/\tau_c - 1)^b$$

where C_n is a coefficient which is related to how consolidated the sediments are, i.e., related to the time between storms. The concentration of suspended matter is e/h added to the background concentration with h as the mean water depth. The concentration of suspended matter is higher in very shallow lakes than in deeper lakes.

Over most lakes there are prevailing wind directions. Loose material eroded during the action of these winds settle all over a shallow lake, but may remain within the vegetation on the leeward shores from which the wind is coming. The soft sediments are thicker here than on the rest of the lake, until a strong wind is blowing from the opposite direction, as is illustrated in Figure 2. Then the thick material accumulated within the vegetation is brought in suspension resulting in high concentration of suspended matter. Sediment distribution depending on prevailing wind directions has been found in Lake Vörtsjärv (Nöges et al., 1999) and Lake Kranke (Borell-Lövstedt and Bengtsson, 2008b). In Lake Kranke shifts from clearwater to turbid state can be related to strong winds from uncommon direction.

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HYDROLOGICAL SIZING OF WATER SUPPLY RESERVOIRS

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Introduction

Surface water resources in lakes, rivers, and artificial reservoirs constitute a vital component of water supply systems in most countries. In particular where rainfall and hence river flows are seasonal, reservoirs are required to regulate the water available for use by storing the water during the period of excess rainfall for release during the period of low or no rainfall. A reservoir, therefore, helps to minimize the temporal variability in the pattern of water

available for use for various purposes including domestic and industrial water supply, irrigation, and in-stream needs, such as water quality enhancement and water pollution control.

To be able to obtain the most out of a reservoir development, the dam must be appropriately sized such that, given the record of inflow at the site, it is able to meet its target demand with an acceptable level of performance. In other words, the reservoir-sizing problem can be thought of as the development of a relationship of the form:

$$K_a = f(Q, D, R) \quad (1)$$

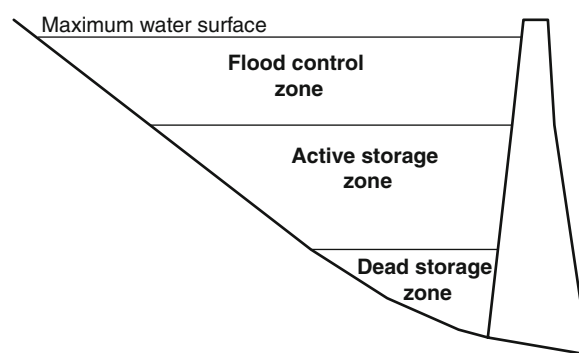
where K_a is the reservoir capacity (or size); D is the outflow (which is a generic term for the demand and other inevitable sinks of water such as evaporation and seepage); Q is the inflow at the reservoir site; R is the level of performance; and $f(\cdot)$ is a functional form.

The functional form in Equation 1 is complex and, except for highly simplified, albeit unrealistic, systems, has no closed form solution. A more practical approach has been to use empiricism; consequently most of the available reservoir-sizing techniques have been based on such empiricism. The aim of this essay is to give a brief yet sufficient outline of the most commonly used empirical methods. In selecting the methods to present, emphasis was placed on ease of use and data requirements. Thus, methods which are readily usable and which are not too demanding in terms of their requirements will be emphasized because such are amenable to be applied in ungauged or sparsely gauged catchments prevalent in less developed economies where exercises in reservoir planning are still common. In more developed economies, current concerns are with better operational management of existing facilities rather than the development of new resources. For readers interested in the more analytically rigorous planning methods and operational tools, reference can be made to McMahon and Adeloeye (2005). Meanwhile, some basic definitions of the commonly used terminologies in the reservoir-sizing problem will be given.

Reservoir sizing terminologies

Storage, S_t

This is the volume of water stored in a reservoir at a given time and used for meeting the various demands placed on the reservoir. The storage, therefore, defines the state of the reservoir at any time, t . More specifically, the storage is often referred to as the active storage, to distinguish it from the dead storage and flood surcharge storage (see Figure 1). In the reservoir-sizing problem, S_t is regarded as a state variable with the upper limit equal to the capacity of the reservoir, K_a . Off-take of water from the reservoir for the purpose of meeting demand is normally made above the dead storage because of the poor quality of water stored in the latter.



Hydrological Sizing of Water Supply Reservoirs,
Figure 1 Storage zones in a water supply reservoir.

Inflow, Q_t

This is the total amount of water flowing into the reservoir in a given time period. The inflow is dominated by the run-off at the catchment outfall, but other sources of water might include direct rainfall on the reservoir surface, diversions from other sources such as through inter-basin transfers, and releases from an upstream reservoir or group of reservoirs.

Demand, D_t

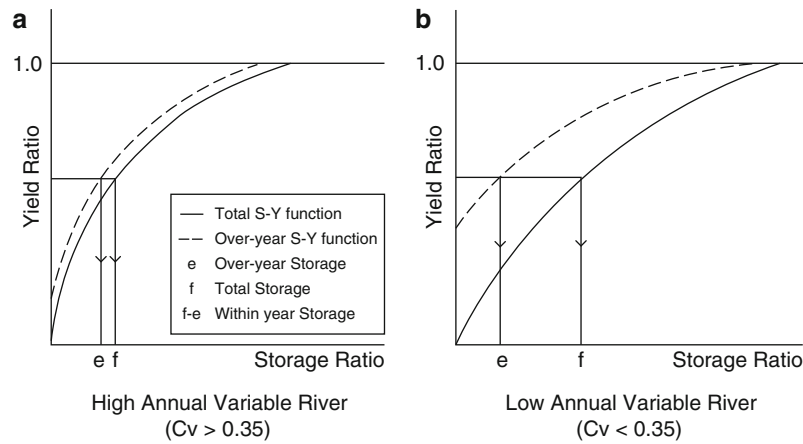
This is the amount of water required from the reservoir in a given period. Other terms used synonymously with the demand are the draft, release, and yield. However, in a strict sense, the demand is different from these other terms in the sense that while the demand might be a fixed quantity, the three latter terms define a variable quantity whose value depends on the way the reservoir is operated. Thus, depending on the state of the reservoir storage, S_t , and the anticipated inflow, the release might be equal to, lesser, or greater than the demand.

Critical period

The critical period is the period of low inflow sequence into a reservoir during which if the reservoir was full at the beginning, it will be empty at the end of the period. The majority of reservoir-sizing techniques are based on the critical period concept because, in reality, any supplementary water provision for the purpose of meeting the demand should only be required over the critical period. For all other periods, the natural river flow is sufficient to meet the demand, and there is therefore no need to store water for release during such periods.

Within-year and over-year storage size

Within-year storage is that required to meet seasonal disparity between inflow and demand, whereas over-year storage is that required for meeting the disparity over several years. The distinction between these two types of storage requirements is important because they require different temporal scale of data to adequately analyze.



Hydrological Sizing of Water Supply Reservoirs, Figure 2 Schematic illustration of a reservoir storage-yield (s-y) function highlighting the effect of annual flow variability.

For example, Figure 2a and b is schematics of a reservoir storage-yield (s-y) function in which both the yield and storage size have been scaled by the mean annual runoff to remove the effect of river size. For low annual variable rivers (i.e., rivers with $C_v < 0.35$, where the C_v is the coefficient of variation of annual runoff and is estimated as the standard deviation of annual runoff divided by its mean), there is significant, additional within-year storage to meet demands in dry months. On the contrary, within-year requirements are minimal in high annual variable rivers (see Figure 2a), and the storage-yield function for such rivers can be developed using annual runoff data; seasonal or monthly runoff data must be used to develop the function for low annual variable rivers to minimize undersizing of the reservoir.

Reservoir performance measures

A reservoir is said to perform satisfactorily if it meets the demand in all time periods; when this is not the case, there is a performance failure. Reservoir performance is traditionally characterized by the *reliability*, *vulnerability*, and *resilience*.

Reliability: The reliability concept can be applied in either the time or volume domain.

Time-domain reliability – This is the proportion of the total time under consideration in which a reservoir will be able to meet the demand without shortage. A general expression for computing time-domain reliability, R_t , is:

$$R_t = \frac{N_s}{N} \quad (2)$$

where N_s is the total number of intervals during which the demand was met and N is the total number of time intervals under consideration. Where annual data are used in the analysis, then N_s becomes the number of successful years and N becomes the number of years in the

simulation period, and the estimated reliability is termed the *occurrence-based reliability* because it represents the average probability of achieving the particular yield in any given year (Klemes et al., 1981) or conversely, the average recurrence interval for the yield, similar to average recurrence intervals used in the study of floods. For time intervals less than the annual, e.g., monthly, the time-based reliability is generally higher than the annual occurrence-based reliability.

The complement of the reliability is the frequency of failure, F , i.e.,:

$$F = 1 - R_t \quad (3)$$

Volumetric-domain reliability – The volumetric reliability, R_v , is calculated as the total quantity of water actually supplied divided by the total quantity of water demanded during the entire operational period, i.e.,:

$$R_v = \frac{\sum_{t=1}^N D'_t}{\sum_{t=1}^N D_t} \quad (4)$$

where D'_t is the actual supply from reservoir system during period t and D_t is the demand during the same period. If the demand is satisfied in all the time periods, then $D'_t = D_t$ for all t and R_v is unity.

Let us investigate the relationship between the relative magnitudes of R_t and R_v . Consider a single failure in the total period N during which the period demand is D_t as usual. The supply during this failure period is, using our usual notation, D'_t where $D'_t < D_t$

Therefore,

$$\text{failure frequency} = \frac{1}{N}$$

and

$$\text{volumetric failure} = \frac{D_t - D'_t}{D_t N} = \frac{1}{N} - \left(\frac{D'_t}{D_t} \right) \frac{1}{N}$$

Thus, unless $D'_t = 0$, i.e., no supply at all during the single failure period, the volumetric failure will always be lower than the occurrence-based failure for any reservoir system that manages to supply some water during failure periods, i.e., $R_v \geq R_t$. The question then arises as to which of the two, time-based or volume-based, to use for planning decision-making. A general advice is to base the initial decision on the time-based reliability while at the same time computing the volumetric reliability. Observations on this volumetric reliability may then be made to adjust further the time-based reliability, e.g., the time-based reliability may be relaxed if the volumetric reliability is very high or made more stringent if the volumetric reliability is too low.

Resilience: The most widely used definition of resilience is by Hashimoto et al. (1982) who defined resilience as the probability that a reservoir system will recover following a failure:

$$\varphi = \frac{1}{\left(\frac{f_d}{f_s} \right)} = \frac{f_s}{f_d}; \quad 0 < \varphi \leq 1 \quad (5)$$

where φ is resilience, f_s is number of continuous sequences of failure periods, and f_d is the total duration of the failures, i.e., $f_d = N - N_s$. Since the denominator $\left(\frac{f_d}{f_s} \right)$ on the right-hand side of Equation 5 is the average duration of continuous failure periods, then the resilience is the reciprocal of the average duration of failure periods. Thus, the longer the average duration of continuous failure periods, either due to a longer f_d or a fewer f_s , the smaller is the resilience and hence the more difficult it is for the reservoir to recover from failure.

Another measure of resilience, which is much easier to estimate than the measure in Equation 5, was recently suggested by McMahon et al. (2006):

$$\varphi = \frac{\bar{D}'}{D} \quad (6)$$

where $\bar{D}'$ is the minimum period release by the reservoir.

Vulnerability: A reservoir performance measure allied to the volume-based reliability is the vulnerability or the impact of failure. Hashimoto et al. (1982) defined vulnerability as the average of the maximum shortfalls occurring in each of the continuous failure periods, i.e.,:

$$\eta' = \frac{\sum_{k=1}^{f_s} \max_{t \in k} (D_t - D'_t)}{f_s} \quad (7)$$

where η' is vulnerability, $\max(\cdot)$ is maximum shortfall during the k th continuous failure sequence, and f_s is the

number of continuous failure sequences in the simulation. A more useful form is the dimensionless vulnerability η , given by:

$$\eta = \frac{\eta'}{D} \quad (8)$$

McMahon et al. (2006) investigated the relationship and possible trade-offs between various measures of reservoir performance using extensive Monte Carlo simulation. They found out that the resilience and dimensionless vulnerability are complementary, i.e.,:

$$\varphi \cong 1 - \eta \quad (9)$$

implying that once one of them is evaluated, the other can be easily inferred. Equation 9 can readily be established if the alternative definition of resilience in Equation 6 is combined with Equations 7–8 (see McMahon et al. (2006) for details).

Other performance indices: a summary

Other performance indices have recently appeared in the literature; the overriding aim of these indices is the derivation of a single index, which will incorporate the combined effects of some of the indices described above (Loucks, 1997). Simonovic (1998) called such integral indices the *figures of merit* (FM), and examples of these are the *drought risk index* (DRI) (Zxongue et al., 1998) and the sustainability index (Loucks, 1997). The DRI is defined as:

$$\kappa = \varepsilon_1(1 - R_t) + \varepsilon_2(1 - \varphi) + \varepsilon_3\eta \quad (10)$$

in which ε_1 , ε_2 , and ε_3 ($\sum_{i=1}^3 \varepsilon_i = 1.0$) are weights that may

be assigned values depending on the relative significance placed by the analyst on each of the three performance indices. If the three indices are weighted equally, then $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 1/3$. Where the vulnerability is the overriding consideration, then more weight can be given to ε_3 relative to the other two weights. The problem with the use of the DRI is that the choice of the weights is subjective.

The sustainability index was defined by Loucks (1997) as:

$$\lambda = R_t\varphi(1 - \eta) \quad (11)$$

where λ is sustainability. The use of multiplication in Equation 11 serves a similar purpose to the weights used in DRI in that it gives an added weight to the statistical measure having the lowest value (Loucks, 1997). For example, if any of these measures are zero, the other indices essentially become irrelevant. Equation 11 is intuitively correct because the sustainability of a reservoir system increases the greater the reliability and resilience, and the smaller the vulnerability. However, although

Equation 11 provides a quantitative measure of sustainability, it is still largely untested with regard to reservoir design and management; other more descriptive sustainability criteria such as fairness, reversibility (of impacts), risk, and consensus (Simonovic, 1998) are still preferred despite their subjectivity.

Methods for hydrological reservoir sizing

The methods to be described can be classified into two broad types: quick or generalized methods and the sequential methods.

Quick (or generalized) methods

The quick methods are fast, back-of-the-envelope methods whose distinguishing characteristic is that they do not require the sequential analysis of complete time series data of inflow to the reservoir. For most of the techniques in this category, only some statistics of the inflow, such as the mean, the coefficient of variation, and the lag-1 serial correlation coefficient, are required as input, in addition to an assumption about the probability distribution function of the inflow.

Dincer procedure

One of the simplest algorithms to size a single reservoir was developed by Dincer (see McMahon and Adeloye, 2005). Dincer assumed a sequence of annual independent inflows with a mean, μ , and standard deviation, σ , and showed that if the annual flows have a normal distribution, then the duration of the critical period (years) is:

$$n_{\text{crit}} = \frac{z_F^2}{4 \left(1 - \frac{D}{\mu}\right)^2} C_v^2; \quad D < \mu \quad (12)$$

and the capacity is:

$$K_a = \frac{z_F^2}{4 \left(1 - \frac{D}{\mu}\right)} \frac{\sigma^2}{\mu}; \quad D < \mu \quad (13)$$

where z_F is the standard normal variate with F probability of non-exceedance, i.e., K_a is the capacity with a probability 100 $F\%$ of running dry (failing) in any year, where F is the failure frequency given by Equation 3. For a known F , the corresponding z_F is tabulated in most standard textbooks on statistics. Alternatively, z_F can be approximated using (Stedinger et al., 1993):

$$z_F = \frac{F^{0.135} - (1 - F)^{0.135}}{0.1975} \quad (14)$$

Where the annual flows are log-normally distributed, the Dincer model can still be used if the parameters μ and σ are replaced by those of a log-normal distribution (as described by McMahon and Adeloye, 2005).

Gould gamma method

For annual flows distributed as gamma, z_F should be transformed to the equivalent gamma variate, g_F , using:

$$g_F = \frac{2}{\gamma} \left[\left\{ 1 + \frac{\gamma}{6} \left(z_F - \frac{\gamma}{6} \right) \right\}^3 - 1 \right] \quad (15)$$

where γ is the sample skew coefficient for the annual flows. For a gamma distribution, $\gamma = 2C_v$. McMahon and Adeloye (2005) contain simplified algorithms for estimating from time series data γ and the other summary statistics required by the Dincer and Gould gamma methods. Furthermore, all the required flow statistics can be obtained easily using Microsoft Excel™.

However, both the Dincer and Gould gamma methods have their limitations. Firstly, by using annual flow statistics, they can only estimate the over-year storage; where within year requirements are significant, an adjustment must be made. Adeloye et al. (2003) and Adeloye and De Munari (2006) have developed techniques for carrying out the adjustment. Other limitations of the two quick methods are:

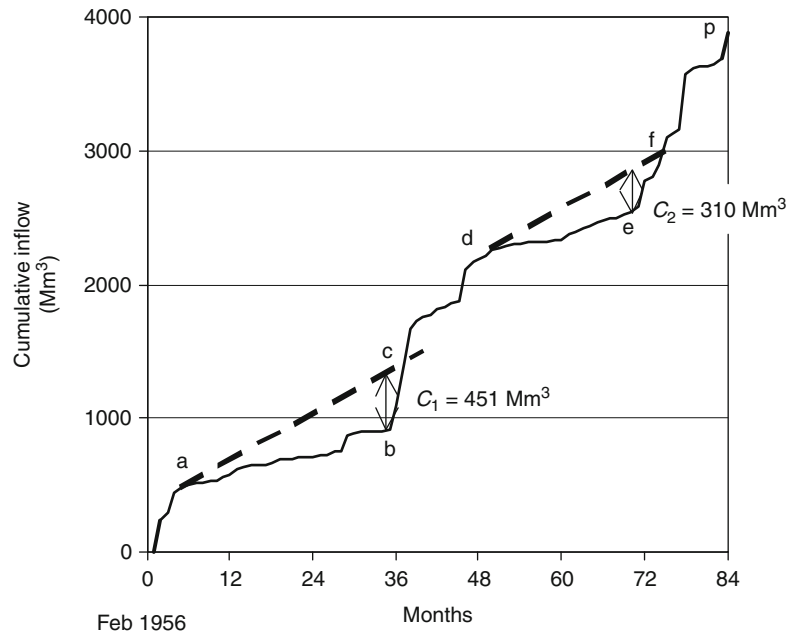
- Neglect of serial correlation in the annual flows
- Neglect of evaporation and other secondary processes

Nonetheless, the techniques are very rapid and useful during preliminary reservoir evaluation studies. Besides, because of their minimal information requirement, i.e., mainly the mean and CV of annual flows, the techniques are potentially applicable at ungauged sites as demonstrated by Adeloye et al. (2003), who also presented procedures for estimating these parameters at ungauged sites.

As remarked before, the Dincer and Gould gamma techniques belong to a broad range of methods known as the generalized storage-yield models. However, while there are other examples of such models – see for example Vogel and Stedinger, 1987; Bayazit and Bulu, 1991; Buchberger and Maidment, 1989; Adeloye and De Munari, 2006 – these two are the easiest to apply, and their estimates can easily be adjusted for within-year requirements as described by Adeloye et al. (2003). Consequently, further details about the other generalized models will not be provided in this report; however, for those interested, additional information is provided by McMahon and Adeloye (2005).

Sequential methods

The procedures presented earlier do not require the sequential analysis of time series data to obtain the storage size. However, except during preliminary planning analysis or when the site of interest is ungauged, most storage sizing determinations require the sequential analysis of inflow time series data. Sequential methods are better because they take into account all the intrinsic characteristics of the data record – serial dependence, variability, and probability distribution function – that affect the storage size. The downside of sequential methods is that by requiring time series data, they are precluded from being applied at ungauged or sparsely gauged sites. Some of the commonly used techniques in this category will now be described briefly.



Hydrological Sizing of Water Supply Reservoirs, Figure 3 Mass curve analysis showing the mass curve (*thick continuous line*), cumulative demand lines (*thick dash line* whose slope = demand per period), and two possible critical periods (a–b, d–e). The maximum difference of 451 MCM is the reservoir size and occurs during the critical period a–c. (Adapted from McMahon and Adeloye, 2005.)

The mass curve procedure

The mass curve procedure was developed by Rippl (1883) and has been used to size reservoirs in many parts of the world over the past century. The method estimates the reservoir capacity as the maximum difference between the accumulated demand and accumulated inflow (or mass curve) during a critical low flow sequence in the historic runoff record at the reservoir site. An example of the mass curve is shown in Figure 3, which also illustrates the concept of the critical period and the determination of the reservoir capacity given the demand. Further information about the step-by-step procedure of constructing the mass curve is provided by McMahon and Adeloye (2005).

The mass curve designs for the worst historic critical drought sequence; if a severer drought occurs during future operational period of the reservoir, the sized reservoir may not meet the demand. This is the biggest limitation of the mass curve approach, i.e., it does not allow the risk of failure to meet the demand to be explicitly evaluated during the design stage.

Other limitations of the mass curve include inability to explicitly accommodate secondary processes effects, e.g., evaporation and seepage, and seasonality in demand, all of which may mean that the reservoir is undersized. The inability to accommodate seasonality in demand stems from the graphical nature of the mass curve which requires that the cumulative demand line must be straight, i.e., a constant demand per period (see Figure 3). Nonetheless, the mass curve is still a very popular method, and the fact that it is graphical means it offers a powerful way of

visualizing the behavior of the reservoir in terms of its filling, emptying, and spilling. In Figure 3, the reservoir is full at “o,” spilling between “o and a,” empty at “b,” full again at “c,” and spilling between “c and d.” Finally, the mass curve can also be used to determine the yield if the capacity is known as described by McMahon and Adeloye (2005).

Sequent peak algorithm (SPA)

The SPA was developed by Thomas and Burden (1963) as the numerical version of the graphical mass curve. The original formulation is described by McMahon and Mein (1986); however, a more easily implemented formulation described by Lele (1987) (see also McMahon and Adeloye, 2005) will be presented here.

In its basic form, the SPA technique estimates the storage size for a failure-free operation of an initially full reservoir over the historical record, i.e., for 100% reliability over the N -year period.

Let:

- C_t be the cumulative sequential deficit at the beginning of period t in a record of N periods
- C_{t+1} be the corresponding deficit at the end of t , i.e., at the beginning of $t + 1$
- D_t be the demand in period t and Q_t be the inflow during t

Then the SPA is implemented in the following steps:

Step 1. Set $C_0 = 0.0$, i.e., assume that the initial deficit is zero, in other words that the reservoir is initially full. (Note: This assumption is common to all critical period

techniques although it is not a problem with the SPA because if it is wrong, it will become apparent during the SPA solution of the problem.)

Step 2. For $t = 1, 2, \dots, N$, calculate:

$$C_{t+1} = \max\{0.0, (C_t + D_t - Q_t)\}$$

Step 3. If $C_{N+1} = C_0$, then go to step 4; else if this is the first iteration, then set $C_0 = C_{N+1}$ and go to Step 2; else STOP: the SPA has failed because gross demand is higher than the average inflow.

Step 4. Estimate reservoir size $K_a = \max(C_{t+1})$ all over $t = 1, 2, \dots, N$.

An example implementation of the SPA is shown in Table 1 for a 15-period inflow sequence (see the second column of Table 1). The constant demand per period is 4.5 units (shown in the third column), and the calculated sequential deficits are shown in the fourth column. The estimated reservoir size is 11 units, which is the maximum of the entries in the sequential deficits column.

The SPA is easy to implement, but although it removes the need to draw a graph and can be used to analyze seasonality in demands and inflows, the technique still suffers from similar limitations of the mass curve technique. Attempts have been made to extend the SPA so that it can design for any desired reliability (instead of the implicit no-failure reliability over the historic record), accommodate evaporation and rainfall fluxes, and analyze multiple reservoirs. Details of the extended SPA are relatively complex and will not be presented in this report; however, for those interested, the necessary details are available elsewhere (see Lele, 1987; Adeloye et al., 2001; Montaseri and Adeloye, 1999; McMahon and Adeloye, 2005).

Behavior analysis

As the name implies, behavior analysis (BA) simulates the behavior of the reservoir taking into account the inflow,

Hydrological Sizing of Water Supply Reservoirs, Table 1
Implementation of the SPA

t	Q_t	D_t	$C_{t+1} = \max\{0.0, (C_t + D_t - Q_t)\}$
0			0
1	5	4.5	0.0
2	7	4.5	0.0
3	8	4.5	0.0
4	4	4.5	0.5
5	3	4.5	2.0
6	3	4.5	3.5
7	2	4.5	6.0
8	1	4.5	9.5
9	3	4.5	11.0 = Capacity K_a
10	6	4.5	9.5
11	8	4.5	6.0
12	9	4.5	1.5
13	3	4.5	3.0
14	4	4.5	3.5
15 = N	9	4.5	0.0 ($C_{N+1} = 0.0$); hence no need for repeating the data record

releases (including secondary processes such as evaporation and direct rainfall), and operating policy for the reservoir. Unlike the methods described previously, which can only handle simple, single reservoir configurations, behavior analysis can handle any multiple reservoir configurations, no matter how complex. BA is perhaps the only reservoir sizing method that considers performance measures other than the time-based reliability such as the volumetric reliability, resilience, vulnerability, etc. Consequently, behavior analysis has been described as the most versatile of all reservoir sizing techniques.

BA is based on the water balance of inputs and outputs from storage as follows:

$$S_{t+1} = S_t + Q_t - D'_t - e_t A_t - L_t; \quad 0 \leq S_{t+1} \leq K_a \quad (16)$$

where S_{t+1} and S_t are the contents of the storage at times $t + 1$ and t , respectively, Q_t is the inflow to the storage during time t , D'_t is the release in volume units during time t , e_t is the net evaporation loss during time t , A_t is the surface area of net evaporation at time t , L_t is the seepage loss in volume units during time t , and K_a is the active capacity of the storage.

The constraint on the RHS of Equation 16 is important because it implies that the storage state S_t of the reservoir cannot be negative or greater than its physical size (or capacity) K_a . Unless the needed data are available, it is customary to ignore the net evaporation and other loss terms when applying Equation 16. Specifically for evaporation, McMahon and Adeloye (2005) describe methodologies for accommodating evaporation losses in a BA if the required data are available.

To use a BA to size reservoir capacity for known demand and performance index, a value for the capacity is first assumed, and the water balance equation is applied sequentially through the data record, subject to the non-negativity and capacity constraints on storage. With K_a assumed, the main decision variable is the release D'_t because its value is either sufficient to meet the demand or not. The decision on the amount of water to release and hence the value of D'_t is based on the operating policy, which in turn is dependent on the amount of water available. Whenever there is sufficient water, the demand can be met; however, when there is insufficient water, a release lower than the demand is made, and a failure performance is recorded. (Sometimes, the operating policy is not as straightforward as this and decision may be made NOT to supply the whole demand in a given period even when there is sufficient water. This is to forestall more catastrophic future failures. This practice is called *hedging*. Arriving at the decision on when and how much to hedge is complicated and beyond the purview of this entry.)

Once a decision about D'_t has been made, the state of the reservoir is then updated using Equation 16, and the analysis moves to the next time period. When the end of the data record is reached, the total number of failure occasions as well as the volume of water shortage are calculated and used to determine the performance

characteristics such as the time and volumetric reliabilities. If the performance index differs from the pre-specified target, then a new reservoir capacity is assumed, and the process is repeated until the obtained performance index is equal to the target.

In essence therefore, the sizing of a reservoir for known yield and performance using a BA is a trial and error process; consequently, the reservoir size solution of BA may not be unique. Indeed, it has been demonstrated by Adeloje et al. (2001) that this non-uniqueness occasioned by the trial and error approach in BA is a principal cause of the misbehavior of BA capacity estimates first noticed by Pretto et al. (1997).

However, BA is much more than a design or planning tool. Indeed, the most common use of BA is the assessment of the performance of reservoir systems for which the main design parameters, i.e., the demand and capacity (or size), are known. In such a situation, the analysis is no longer a trial and error procedure, and the outcome is unique information about the performance of the reservoir. If the performance is not satisfactory, then changes can be made to the design variables to achieve the desired performance.

For the above reasons, McMahon and Adeloje (2005) (see also Adeloje et al., 2001) have recommended that the use of BA be restricted to performance evaluation of existing facilities. For design purposes, the SPA described previously and its extensions (see McMahon and Adeloje, 2005) are recommended.

Sizing of reservoirs – other possibilities

The present discussion will be incomplete without outlining other possibilities for the hydrological sizing of water supply reservoirs. These include:

1. The use of stochastically generated data
2. The use of optimization (or operations research) methods
3. The use of transition probability methods

1. Stochastically generated data

All of the methods described in the earlier sections have either used single historic time series data or statistical parameters estimated from such. As adumbrated while discussing the mass curve technique, such an approach is not adequate because it fails to anticipate future droughts which could be more severe than that contained in the single historic sequence. In other words, the estimate of the capacity obtained from a historic data record is a realization of a stochastic variable, and other realizations of this variable can be obtained by analyzing other realizations of the historic record.

The generation of other realizations of the historic record uses a technique known as stochastic hydrology or Monte Carlo simulation. Without going into excessive detail, this will entail:

- Formulating a stochastic model for the inflow runoff process, e.g., for annual flow, a commonly used model is the lag-1 autoregressive (AR-1) (or Markov) model.

This is best applied if the annual flows have a normal distribution; where the flows are not normally distributed, suitable transformations, e.g., the log-normal or the Box–Cox (see McMahon and Adeloje, 2005), can be used to obtain approximate normally distributed flows.

- Calibrating the model by estimating its parameters, usually the mean, Cv, skewness, and the auto-correlation coefficient.
- Using the model to generate a large number of replicates of the historic data, with each replicate having the same length as the historic. There is no hard and fast rule on the number of replicates; however, 1,000 replicates should suffice.
- Determining for each replicate the storage size using an appropriate technique, e.g., the mass curve, SPA, or a BA. The 1,000 size estimates then constitute the “population” of sizes.
- Analyzing the “population” of sizes to determine summary statistics such as the mean, standard deviation, Cv, median, skew, empirical distribution function, various quantiles, etc., of reservoir size.

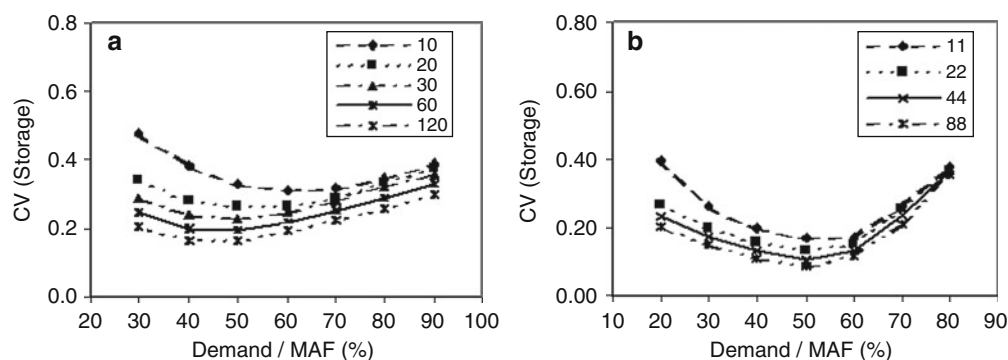
The standard deviation (or better still the Cv) estimated in the fifth step above is a measure of the standard error (or uncertainty) in the capacity estimate. This uncertainty will increase as the record length increases, as illustrated in Figure 4.

The above description assumes that seasonality in inflow and demand is insignificant. Where there is a strong inflow seasonality, then seasonal flows must be generated stochastically, either directly using a seasonal stochastic model or indirectly by disaggregating from generated annual flows (see McMahon and Adeloje, 2005). Another issue of note in using the Monte Carlo approach relates to parameter uncertainty. The parameters for driving the stochastic model are subject to uncertainty by virtue of the fact that they are obtained from a limited historic data record. Consideration of parameter uncertainty introduces an additional layer of complexity, but this may be unavoidable in certain situations, e.g., in highly variable rivers (see Montaseri and Adeloje, 1999). McMahon and Adeloje (2005) describe the procedures for incorporating parameter uncertainty in AR-1 flow generation models.

2. Optimization

Constrained optimization solution of reservoir sizing problems is also widely practiced as reviewed by Yeh (1985). An optimization formulation requires an objective function and a set of constraints. Depending on the particular problem, solution is then sought using linear programming (LP), dynamic programming (DP), non-linear programming (NLP), or some of the emerging techniques based on evolutionary programming of which genetic algorithms (GA) are the most popular.

Of the available solution algorithms, the LP is the most commonly used for reservoir sizing. As the name implies,



Hydrological Sizing of Water Supply Reservoirs, Figure 4 Effect of runoff record length on the variability of reservoir size estimates for (a) a river in Yorkshire, England, and (b) a river in Urmia Region, northwest Iran. MAF is the mean annual flow. (Adapted from Montaseri and Adeloye, 1999.)

both the objective function and the constraint equations must be linear in the decision variables for linear programming; otherwise appropriate linearization of these functions must be carried out to apply LP.

For the typical sizing of a single reservoir, the objective function is the minimization of the capacity, i.e.,:

$$\text{Min } (K_a) \quad (17)$$

The associated constraint equations are:

Reservoir mass balance

$$S_{t+1} = S_t + Q_t - D_t \quad (18a)$$

Size constraint

$$S_{t+1} \leq K_a \quad (18b)$$

Non-negativity constraint

$$0 \leq S_{t+1} \quad (18c)$$

Other constraints might include a limit on the size of K_a due to environmental considerations and a limit on S_{t+1} in certain seasons to accommodate, e.g., flood water. McMahon and Adeloye (2005) contain examples of several LP problem formulations for the planning of reservoir sizing. An attractive and unique feature of optimization is that the objective function can contain economic and non-economic factors, implying that costs and benefits (both financial and environmental) of the reservoir development can be considered in the size planning analysis. For single reservoir problems, consideration of actual costs and benefits in the objective function is not crucial because a minimization of the reservoir size is the same as a minimization of the cost for a single variable problem. This may not be the case for complex, multiple reservoir configurations.

3. Probability matrix method

The transition probability matrix (TPM) methods model the reservoir states (or storage) directly as a stochastic process. This is the main difference between these approaches and those described earlier in which the focus was the inflow.

The transition probability matrix method emanated from the seminal work on the theory of storage by Moran (1959), and although refinements to the method have since occurred (see McMahon and Adeloye, 2005; Zsuffa and Galai, 1987), the method is not as popular as the sequential methods based on streamflow analysis. Indeed, concerted efforts in developing the TPM have been restricted to parts of Eastern Europe, notably in the countries of the former Soviet Union. Nonetheless, the TPM methods do offer some added benefits in that the estimated size is independent of any assumptions made about the initial starting conditions and secondly, the performance (e.g., failure probability) can be computed either at steady state or as a time-dependent function (McMahon and Adeloye, 2005).

Conclusion

Hydrological sizing of water supply reservoirs is important to ensure that the reservoir will meet the demand with an acceptable level of performance. The methods described in this short article are by no means the only ones available. However, they have been selected because they are among those commonly applied, and some of them, by requiring limited data input, are readily applicable at ungauged and sparsely gauged reservoir development sites. This is particularly significant in developing country economies of the world where the problem of lack of data is the most serious and where paradoxically the need for planning and design of new reservoirs is still prevalent.

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Cross-references

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HYDROPOWER

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Description

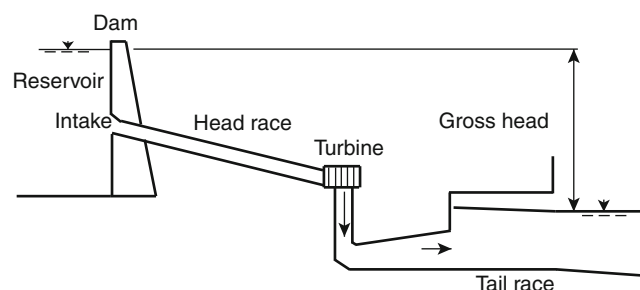
In a hydroelectric power plant, the potential energy represented by the difference in elevation between a headwater surface above and the tailwater below the power plant is transferred to electricity by letting the water pass through a turbine which in turn drives an electric generator. This energy originates from the solar radiation which is the driving force of transport of moisture evaporated from the oceans and inland lakes, and transport of moisture which condensate in the atmosphere forming precipitation on high altitudes.

The main components in a hydroelectric power plant are (Figure 1):

The dam, with the purpose of blocking the watercourse so that the water intended for the hydropower production does not pass through the power plant via the natural river channel. It is intended to raise the water level in the watercourse, thus creating an increased head and a reservoir.

The headrace conduit, conveys the water from the reservoir to the turbine. The conduit can be a channel, flume, penstock, tunnel, or combinations of these. The length of the headrace can vary from a few meters to several kilometers.

The intake, located in the upstream end of the headrace, is the transition between the reservoir and the headrace. In the intake is a trash rack preventing debris, ice, fish,



Hydropower, Figure 1 General layout of a hydropower plant.

etc., from entering the headrace and a gate as well for closing of the intake.

The *power station* is where the energy of the water is transferred to mechanical energy in the turbine, and from mechanical energy to electrical energy in the generator.

The *tailrace* conveys the water from the power station back to the natural watercourse. It can be a channel or tunnel or a combination and have lengths as that of the headrace, from meters to several kilometers.

Hydroelectric power plants can be classified in several ways, for example, in terms of installed capacity (micro, mini, or ordinary hydro), in terms of head (low, medium or high head) or in terms of operative mode (storage, run of river or pumped-storage). In the storage plant type, water from the wet season is stored in a reservoir and used for power production during the dry period. In the run of river-type plant, the storage capacity is limited, and the water in the stream is used only as it comes. In the pumped-storage plant, water is pumped from a tailwater reservoir to a headwater reservoir on a higher elevation during periods with a small energy demand (e.g., at night when the cost of energy is small). During periods with high energy demand (e.g., daytime when the value of the energy is high) the pump is reversed to act as a turbine as the headwater reservoir is emptied.

The difference in elevation between the water level in the upstream reservoir and the water level at the point in the water course where the water is conveyed back after having passed the turbine is called the *gross head*. The head utilized for energy production after deducting the energy losses intakes, head and tailrace conduits, etc., is called the *net head*.

The power P (W) produced in a hydroelectric power plant $P = \eta \rho g Q H$, where H = net head (m),

Q = flow rate (m^3/s), g = acceleration of gravity (m/s^2), ρ = density of water (kg/m^3), and η = efficiency factor, considering energy losses in the turbine, generator, and transformer.

Major advantages of hydropower are that it is renewable, produces no carbon dioxide except for a limited amount during construction, and is cost effective.

Some disadvantages of hydropower reservoirs are loss of land, damage on the ecosystem, and sometimes relocation of people living in the planned reservoir area. Reservoirs can produce methane if forests have not been cut before filling of the reservoir, particularly in tropical regions. If the river carries sediment that is deposited in the reservoir, the water passing the power plant contains very little sediment, which can lead to scouring of the beds and banks of the river downstream of the dam.

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ICE COVERED LAKES

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Ice formation

Lakes at high latitudes or high altitudes are ice covered part of the year; typically from November to April and in the very north sometimes from October to early June. Arctic lakes may be ice covered throughout the year. When there is a regular ice cover for several months, the ice thickness reaches more than $\frac{1}{2}$ meter. At mid latitudes occasional ice cover may appear for short periods several times during a winter. Where there is a stable ice cover, ice roads are prepared. Fishing is done also at commercial scale. Ice covered lakes are used for recreation.

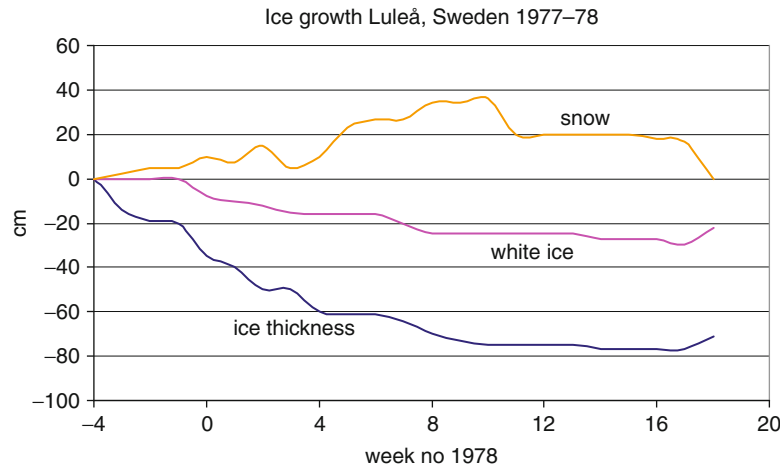
Ice on a small lake is formed rather quickly after the surface water is cooled down to the freezing point – most often after a cold night with no wind. It takes much longer time for a large lake to freeze-over than a small lake, since relatively warm water is brought to the surface during the more intense mixing in a large lake. Ice on lakes grows in a static way; there is no horizontal transfer of ice but the ice grows in the vertical. Ice is produced as black ice, when heat is lost to the cold atmosphere from the water underneath the ice, or as snow ice, when the ice is suppressed under the water surface by heavy snow and water freezes in the slush layer in the snow on top of the ice. Once ice is formed it grows rather quickly in the first weeks until the ice cover and snow on the ice insulate the water from the atmosphere; the rate of ice growth is slowed down. The heat lost from the water to the atmosphere must be taken from the latent heat released when ice is formed, since the water just below the ice is at the freezing point.

Ice formed from the underside of the ice sheet has crystals with columnar structure; it is possible to see through the ice. Such ice is called black ice. Ice can also be formed in a slush layer between the snow and the top of the ice. When the weight of the snow is more than the lifting force from the ice, the ice cover is forced under the water surface and water enters into the snow which becomes saturated with water. When this slush layer freezes, snow ice or white ice is formed. The crystals in this kind of ice are randomly distributed. This ice is not transparent but looks somewhat like milk. An example of ice growth is shown in [Figure 1](#) from a bay in the Luleå archipelago (almost fresh water).

The ice on a lake has ecological consequences. Since there is no exchange with the atmosphere, the oxygen content of the water decreases and the bottom layers may be completely depleted of oxygen. Man's impact on lake ice is mainly from release of oxygen consumption substances, which increases the rate at which the lake water is depleted in oxygen. All releases from industries and waste water treatment plants and also the increased winter flows in regulated rivers have local effects on the ice cover.

Thermal regime

The thermal regime of ice covered lakes considers the heat fluxes to and from a water body without direct contact with the atmosphere, the temperature distribution over the depth, and how it changes during the ice covered period. In the autumn after the surface water is cooled to 4°C and the water has turned over, the warmest water in a lake is that of the highest density. The surface water is colder than the bottom water. If there is a very cold period shortly after the turnover, a wind-sheltered lake may freeze-over when the water not far from the surface and downward is still 4°C. In another year the turnover may be followed by an extended windy period with air



Ice Covered Lakes, Figure 1 Observed ice growth in the inner archipelago in Luleå, Sweden. Snow depth on the ice is shown and separately the snow ice growth. The dotted line is the computed ice thickness using a degree-day approach. Measurements by the author.

temperatures fluctuating around 0°C resulting in a reduction of the lake water temperature down to considerable depths. The initial temperature profile after freeze-over is quite different for the two situations.

Once a lake has a stable ice cover the lake water is more or less insulated from the atmosphere. The heat lost to the cold atmosphere is taken from the latent heat released from the ice growth. There is a small sensible heat flux from the water to the underside of the ice. The major heat flux in an ice covered lake is that from the sediments to the lake water. Heat stored in the sediment from summer to winter is released. The lake water temperature increases in the course of the winter, see Figure 2 from Lake Velen in Sweden. Lakes in cold long winter climate tend to be warmer than lakes in milder climate with less stable winters. In the milder climate the lakes freeze-over later, when they have cooled down throughout the vertical, and also in the milder climate the lake ice may break up several times during winter allowing wind mixing and heat losses directly to the atmosphere. The bottom temperature is often 4°C already at the time of freeze-up; if not, because of the contribution of heat from the sediments this temperature is approached in the course of the winter. The bottom temperature may even be slightly higher than 4°C, due to diffusion of solutes from muddy sediments.

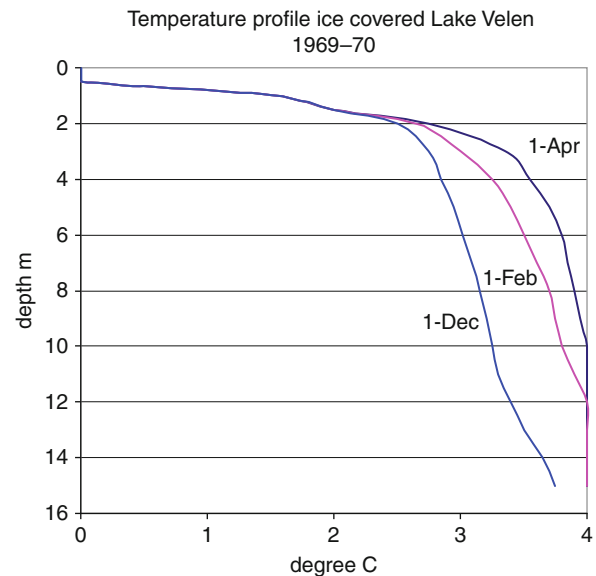
The change of the heat content, dH/dt in an ice covered lake is

$$\frac{dH}{dt} = \rho c_p \int A(z) \frac{\delta T}{\delta t} dz$$

$$= (H_{sed} + R_{netsol} - H_{ice})A_{surface} + H_Q$$

where T is temperature, z vertical distance, t time, c_p specific heat capacity, and ρ is density of water and $A(z)$ is area at depth z .

The sediment heat flux per unit area, H_{sed} , is the most important heat flux. The sediment heat flux at shallow



Ice Covered Lakes, Figure 2 Temperature in ice covered Lake Velen, mean depth 6.5 m, max depth 17 m, lake area 2.8 km².

water may be in the range 4–10 W/m² in early winter and reduce to 1–3 W/m² in late winter. At the deep part of a lake it is smaller, 2–3 W/m² in early winter and less than 1 W/m² prior to breakup.

The heat advection, H_Q , with the through-flow is very small in most lakes, since the river through-flow per unit lake area is small and the temperature of the inflowing river water is very close to 0°C. In narrow fjord lakes the flow per unit area may be substantial. However, in such lakes a thermocline develops so that the river runs through the lake within a top layer of 0°C temperature. The heat loss, apart from that of the heat loss with outflowing water,

is the sensible heat flux from the water to the underside of the ice, H_{ice} . A pronounced temperature gradient develops close to the underside of the ice. A viscous sublayer develops. The heat flux is $1\text{--}2\text{ W/m}^2$ in most lakes but can be rather much higher in late spring, when solar radiation penetrates the ice. The intensity of the solar radiation, which penetrates the ice is denoted $R_{net\text{sol}}$.

In spring when the snow on the ice melts, solar radiation can penetrate the ice and heat the water below. Although only a small fraction of the solar radiation reaches the lake water, the flux is higher than the other fluxes in an ice covered lake. Depending on the ice character and the ice thickness and time of year the solar radiation penetrating the ice is $10\text{--}40\text{ W/m}^2$, partly compensated for by increased heat transfer from the water to the ice.

Circulation and mixing in ice covered lakes

Knowledge about circulation processes in lakes is essential when planning for the use of a lake for water supply or receiving waters. The conditions controlling the dynamics of ice covered lakes are different from those of an ice-free lake. The ice cover prevents direct generation of wind mixing. The water movements are much determined by thermal processes and by the vertical movement of the ice cover. There are also oscillations caused by the setup of the ice surface by the wind. River inflows induce some circulation close to the inlet. While the currents in ice-free lakes are typically 2% of the wind speed, that is, 20 cm/s when the wind is 10 m/s, the currents in an ice covered lake are very much lower. The oscillation movements may be 1 cm/s back and forth. The currents caused by thermal processes are of the order mm/s or even less. Still these movements result in vertical mixing and changed temperature conditions in the course of the winter.

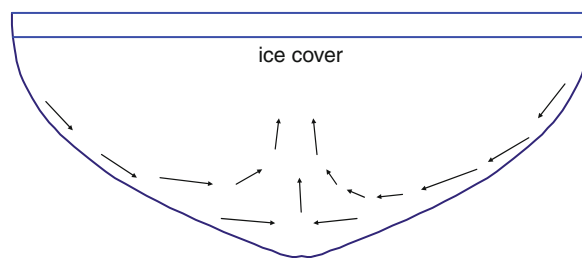
The thermal conditions and the heat fluxes are responsible for convection and mixing of different character. Heat accumulated in the sediments during summer is released to the water in ice covered lakes. When the water gains heat from the sediment it becomes warmer and denser and the water slides downward generating a large convection cell. A different form of more local convection is generated for a short period in the late spring, when solar radiation can penetrate snow-free ice. Density instabilities arise and a top mixing layer develops.

Water which gains heat from the sediment near the shores moves slowly along the bottom toward the deeper parts of the lake, generating large convective circulation cells as shown in Figure 3. The velocities involved seem to be well below 1 mm/s. It is possible to determine a vertical mixing coefficient from the change over time of the vertical temperature profile. The thermal vertical diffusivity is well below $0.1\text{ cm}^2/\text{s}$. The bottom water is mixed due to the convection induced by the heat flow from the sediments. However, once the water has reached the temperature of maximum density, 4°C , the water does not take part in the mixing process; the convection takes

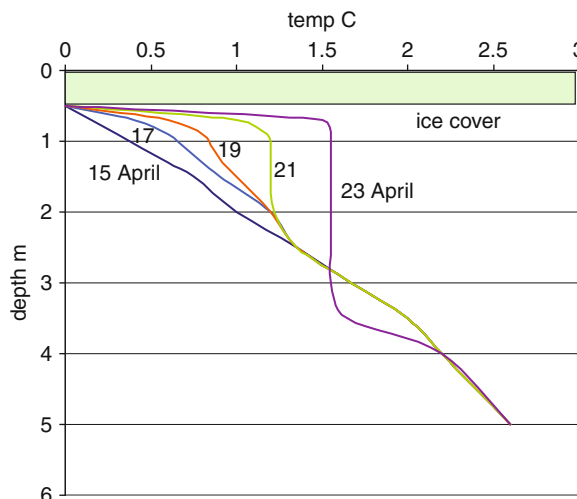
place above this 4°C water. The bottom water in subbasins of a lake may be isolated from the water in the main basin and remain stagnant for many months.

When the solar radiation is able to penetrate through the ice, the water below the ice gains heat and becomes denser than the water further down. Convective mixing is initiated as the warm water sinks. A mixed layer may develop down to considerable depths depending on how far the shortwave radiation reaches, thus depending on the extinction coefficient of the lake water and how much solar radiation penetrates the ice. The mixed layer deepens rather fast, maybe 0.5 m/day . An example of deepening of the mixed layer is shown in Figure 4.

When a wind acts on the ice of a lake, the ice cover is tilted and oscillates. The water particles underneath are forced to move back and forth over short distances, in the order of meters. The maximum velocities in lakes $1\text{--}10\text{ km}^2$ seems to be $1\text{--}3\text{ cm/s}$. The net movement is close to nil, but mixing occurs and particles are dispersed. Some kind of oscillatory currents are always present in ice covered lakes and they significantly contribute to the



Ice Covered Lakes, Figure 3 The principle of large-scale convective circulation generated by heat flux from sediment to water.



Ice Covered Lakes, Figure 4 Convective mixing in Lake Vendyurskoe due to penetration of solar radiation through the ice. Ice thickness 0.5 m.

horizontal mixing. Dye experiments in Swedish lakes, where the oscillation period is about 20 min, have shown that the horizontal dispersion coefficient is in the range 10–200 cm²/s.

A river which runs through a lake generates currents, but after initial mixing near the inlet the river water can be traced only if the river is large. In ice covered lakes, thinner ice on the right-hand side indicating upwelling of warm bottom water with secondary currents induced as an effect of the Earth's rotation has been observed, but most studies show that the current is rather uniformly directed in the upper part of a cross section. When the river flow is large and the lake elongated like a fjord lake, a cold top layer, where the flow takes place, develops over a pronounced thermocline separating the cold layer from a warmer bottom layer.

Summary

Although a lake is ice covered there is mixing and slow currents below the ice. Currents are generated by river through-flow, by oscillation of the ice cover, and by heat released from the sediments. The net currents are of the order mm/s, but still important for the vertical mixing and the development of the temperature profile. The knowledge of the thermal conditions in lakes is essential when planning for water intakes, so that desirable water is provided, or planning for discharge of effluents, so that recirculation is avoided. Withdrawal and release of water may affect the thermal conditions and generate mixing. Regulation of rivers causing winter flows to be higher than the natural ones may influence the temperature in an ice covered lake.

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Cross-references

[Arctic Lakes](#)
[Circulation Processes in Lakes](#)
[Ice Formation on Lakes and Ice Growth](#)
[Lake Ice](#)
[Mixing in Lakes](#)
[Surface Seiches](#)
[Thermal Regime of Lakes](#)

ICE FORMATION ON LAKES AND ICE GROWTH

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Description

Ice forms when the surface water temperature drops to the freezing point. In calm water, the ice grows fast from the shore outward. A small lake becomes ice covered overnight. As long as the ice is thin, it may be broken by strong winds. Lake ice grows in a *static way*, which means that the ice production is only within a vertical and a consequence of vertical heat losses to the atmosphere. The ice is not progressing in any horizontal direction due to currents or floating ice.

When there is no or little snow on the ice, the ice grows from the bottom of the ice cover. *Black ice* or columnar ice is produced. The ice is transparent with the molecules oriented vertically. Heat lost through conduction through

the ice cover, and the snow above is taken from the heat released when ice is produced. The lower the air temperature is, and the thinner the ice is, the faster the ice growth is.

After heavy snowfall, the snow on the ice may become too heavy to be supported by the ice cover without the ice cover being suppressed under the water surface. Water enters into the snow. A slush layer of saturated compressed snow is formed on top of the ice and below the dry snow. Now the heat loss to the cold atmosphere is compensated, for by ice formation within this slush layer, *snow ice* or white ice is formed. This ice has a milky character. The molecules are randomly distributed. The typical winter condition with thick black ice as the lowest layer, snow ice above, and snow on top of the ice is illustrated in the [Figure 1](#).

Since the heat is lost to the atmosphere through conduction, it is fairly easy to estimate the ice growth. The heat loss is

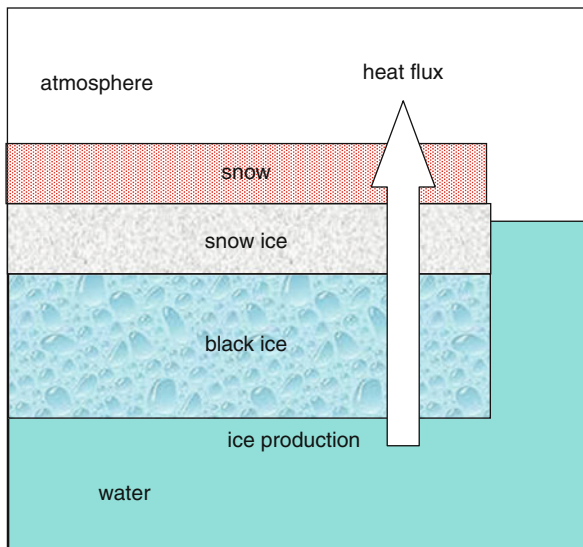
$$H_{\text{loss}} = \frac{-T_a}{h_{\text{ice}}/\lambda_{\text{ice}} + h_{\text{snow}}/\lambda_{\text{snow}} + m}$$

where T_a is the air temperature, h with different index denotes thickness, λ denotes heat conduction coefficient, and m is surface resistance. The surface resistance is of importance only just after lake freeze-over unless the snow surface temperature deviates much from the air temperature.

The heat generated through ice production is

$$H_{\text{generated}} = \phi_i F \frac{dh_i}{dt}$$

where F is latent heat of fusion, ϕ_i is density of ice, and t is time.



Ice Formation on Lakes and Ice Growth, Figure 1 Typical lake ice conditions.

When there is no snow on the ice, putting the generated heat equal to the heat loss, the ice thickness is (initial ice thickness = 0) described with a degree-day approach as

$$h_i = C S^{1/2}$$

where S is number of negative degree-days, i.e., accumulated daily negative temperature, and C is a degree-day coefficient which is found when putting the generated heat equal to the heat loss,

$$C = \left(\frac{2\lambda}{\phi_i F} \right)^{1/2}$$

with λ as λ_i when the ice is free from snow. If not, an effective value must be used, which can be determined from the heat loss equation above. The degree-day coefficient is $3.5 \text{ cm}/(^{\circ}\text{C-d})^{1/2}$ for snow-free ice. For the more common situation with snow on the ice, C is about $2 \text{ cm}/(^{\circ}\text{C-d})^{1/2}$.

The snow depth on lake ice is restricted by the capacity of the ice to support the snow load without the ice surface being submerged under the water surface. From Archimedes principle, it is easily found that the maximum snow depth can not ice over a period longer than a few days is

$$h_{\text{snow}} = \frac{\phi_{\text{water}} - \phi_{\text{ice}}}{\phi_{\text{snow}}} h_{\text{ice}}$$

For typical density of snow on ice, relative density 0.3, the snow depth can not exceed 0.3 of the ice thickness.

From the degree-day equation, it is clear that lake ice grows slower and slower in the course of the winter. In an environment where it snow regularly and the air temperature is almost constant -5°C , the ice grows to 12 cm in a week, to 17 cm after 2 weeks, 24 cm after a month, 35 cm after 2 months, and 42 cm after 3 months.

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Cross-references

[Antarctic Lakes](#)
[Arctic Lakes](#)
[Finnish Lakes](#)
[Ice Covered Lakes](#)
[Icelandic Lakes, Physical Characteristics](#)
[Ladoga Lake and Onego Lake \(Lakes Ladzhskoye and Onezhskoye\)](#)
[Lake Ice](#)

ICELANDIC LAKES, PHYSICAL CHARACTERISTICS

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Introduction

Iceland is a 103,000-km² volcanic island situated on the Mid-Atlantic Ridge, just south of the Arctic Circle. Because of its geographical location, the country boasts both of glaciers and volcanos, earning itself the nickname “country of fire and ice.”

Icelandic surface waters are classified based on their source. Sixty percent of the annual runoff is direct, the remainder is evenly divided between springwater and glacial meltwater (Bjornsson et al., 2008). Lakes cover 2.7% of the country’s surface area, ninety percent of which are smaller than 1 km² (Adalsteinsson, 1987). Lake Thorisvatn is the largest lake (88 km²). Other largest and best known Icelandic lakes summarized in Table 1. Lake Thingvallavatn and Lagarfljot, both deep lakes, with a residence time of almost 1 year, and shallow. Lake Myvatn, with a residence time of approximately 1 month.

Icelandic lakes have provided many important socio-economic functions in the past and present. Considering the four largest lakes, Lake Thorisvatn serves as a storage reservoir for hydroelectricity production. Lake Thingvallavatn and Lake Myvatn (shown on Figure 1) are major touristic attractions, renowned for their wildlife, landscapes, and recreational fishing. The ice-covered Lake Lagarfljot was an important transportation route in the wintertime (Hallgrímsson, 2005).

Building upon the extensive research conducted in Lakes Thingvallavatn, Lagarfljot, and Myvatn, this entry discusses some of the physical features distinguishing Icelandic lakes from others. First, the meteorology and annual thermal cycles are introduced. Then, the fate of groundwater and glacial inflows is discussed. Water circulation in shallow and deep lakes is subsequently contrasted. Lastly, observations and predictions of physical limnological changes due to global warming and human activities are presented.

Meteorology

The Icelandic climate is influenced by the warm waters of the North Atlantic Current. The annual temperature cycle

is moderate, considering the northern location, with monthly mean air temperatures in lowlands (<400 m a.s.l.) ranging from −2°C in winter to 9°C in summer. The maximum average daily temperature in summer time is 16°C (Bjornsson et al., 2007). The climate is also characterized by strong winds, with monthly mean wind speeds ranging between 2 and 7 m/s, and frequent precipitation (Andradóttir, 2008; Bjornsson and Jonsson, 2003).

Thermal cycle

Icelandic surface waters have been found to follow a similar seasonal thermal cycle as air, reaching temperatures as high as 10–14°C in summer (Rist, 1990). Vertical temperature profiling suggests that the majority of Icelandic lakes do not undergo a persistent summer stratification (Malmquist et al., 2010). This is particularly true for shallow systems (<30 m) where wind mixing prevents the formation of a seasonal thermocline. The 100 m deep Lake Thingvallavatn and Lake Lagarfljot, are known to stratify in summer. Their summer stratification is both short lived, lasting solely 2–3 months, and weak with a gradient of 1–3°C across the thermocline (Adalsteinsson et al., 1992; Andradóttir, 2008; Helgason and Axelsson, 2009). The thermal stratification starts developing in June and is fully established by early July. The stratification is destroyed during fall turnover in September, after which the lake water cools uniformly down to 0–2°C. Once this temperature has been reached, the lakes may begin to freeze.

Historical research suggests that the duration of the ice cover varies significantly between lakes of different depths. Table 2 demonstrates, for example, that Lake Thingvallavatn, with maximum depth exceeding 100 m and long residence time (see Table 1), was, on average, ice-covered for 3 months. In contrast, shallow Lake Myvatn began freezing in fall and stayed frozen for approximately 6 months. This difference can be explained by the larger thermal inertia of the deeper Lake Thingvallavatn, which results in slower response to convective cooling. Limited vertical temperature measurements have been performed during periods of ice cover. The few winter profiles from Lakes Thingvallavatn and Myvatn suggest that the water column was inversely stratified, with mean temperature around 1°C. Hence, deep lakes, such as Lake Thingvallavatn, are classified as dimictic, and shallow lakes, as polymictic.

Icelandic Lakes, Physical Characteristics, Table 1 Physical dimensions of largest Icelandic natural lakes

Lake	Lat.	Z (m a.s.l.)	A (km ²)	Mean depth (m)	Max. depth (m)	Residence time (days)	Formation
Thingvallavatn ^a	64°10'	100	82	34	114	330	Subsidence, hyaloclastite and lava dam
Lagarfljot ^b	65°10'	20	53	51	112	270	Glacier-eroded valley lake
Myvatn ^c	65°35'	277	37	2	4	27	Glacier-eroded depression and lava dam

Primary sources: Rist (1975, 1990).

Secondary sources: ^aAdalsteinsson et al. (1992), ^bAdalsteinsson (2010): residence time after damming, ^cOlafsson (1979)



Icelandic Lakes, Physical Characteristics, Figure 1 Lake Myvatn in Northern Iceland (Photo: Arni Einarsson).

Icelandic Lakes, Physical Characteristics, Table 2 Historical winter limnology data in deep lake Thingvallavatn and shallow Lake Myvatn

Lake	Ice cover		Study period	Winter water Temperature (°C)
	Duration (days)	Timeframe		
Thingvallavatn ^a	95	January to April	1951–1990	1–2
Myvatn ^b	189	October to May	1915–1977	0–3

Sources: ^aRist and Olafsson (1986), Adalsteinsson et al. (1992). ^bRist (1979), Olafsson (1979)

Groundwater and glacial inflows

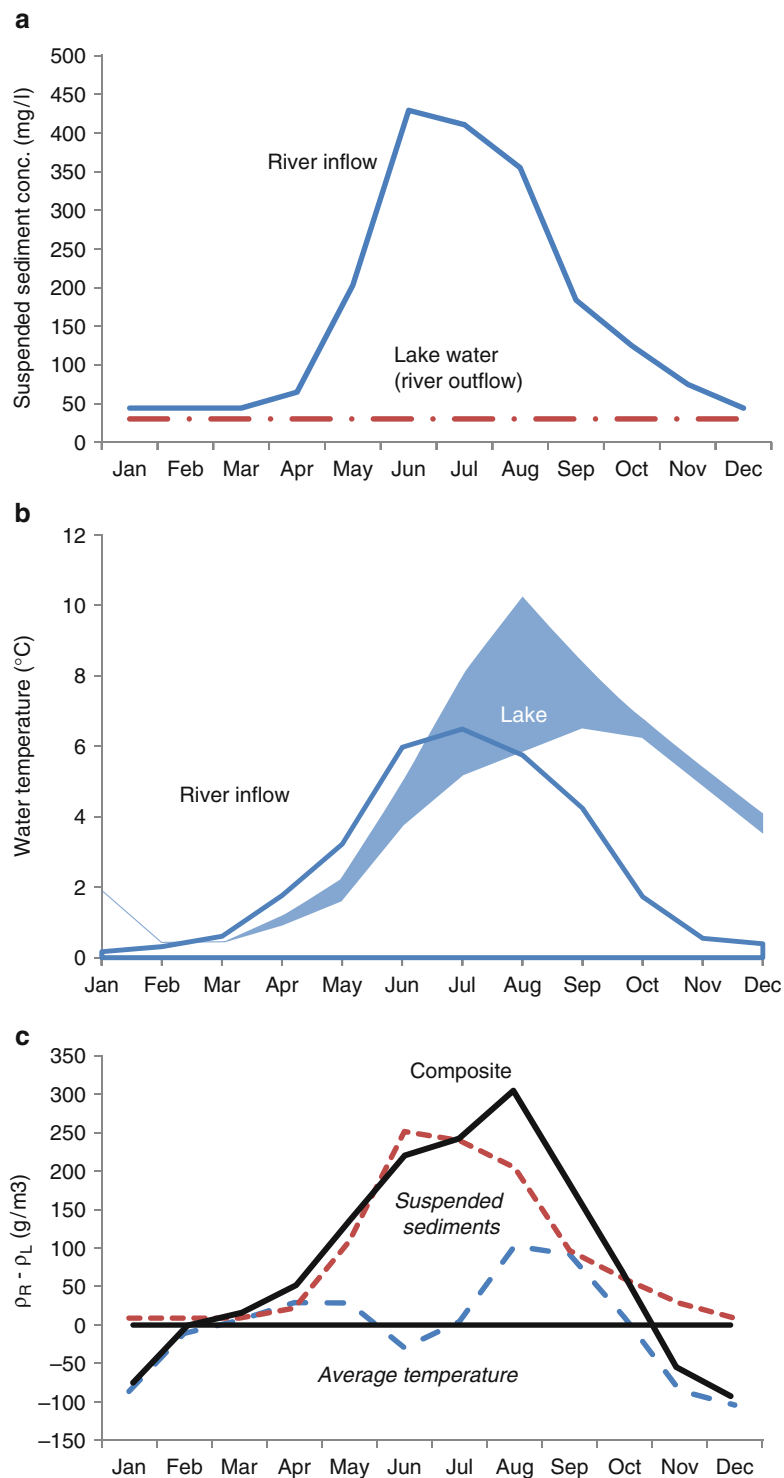
Inflow dynamics

Inflow dynamics – that is, whether inflows enter as surface intrusions or submerged underflows – is determined by the density of the inflows relative to the lake. Icelandic lakes are unique in that many of them are fed by groundwater and/or glacial rivers. The different physical and chemical composition of these sources influences their fate and lake water quality.

First, consider Lake Thingvallavatn and Lake Myvatn, both of which are situated on the neovolcanic rift zone which crosses Iceland from SW to NE. The lakes' catchment areas are mostly postglacial lavas transected by numerous faults and fissures. Precipitation and glacial melt percolate directly into the highly permeable volcanic strata. The mineral-rich water, thus, enters the lakes through warm (>25°C), moderately warm (10°C), and/or cold (3–5°C) subsurface springs (Olafsson, 1979; Adalsteinsson et al., 1992). The origins, characteristics, and quantities of the groundwater inflows to the lakes have been assessed through physical and chemical observations, tracer studies, and groundwater modeling (Kristmannsdottir and Armannsson, 2004; Olafsson, 1992; Vatnaskil Consulting Engineers 2000). The inflow dynamics is found to be primarily governed by the

temperature anomaly between the spring and lake water (Andradottir et al., 2009). Unlike surface water, which varies from 0°C to 2°C temperature in winter and from 10°C to 14°C in summer, as discussed earlier, groundwater temperature remains constant over the course of the year. Consequently, the warm spring water with temperatures exceeding 15°C enters the lakes as a surface intrusion independent of season. Conversely, the cold spring water with temperature close to that of maximum density (3–5°C) enters the lakes as a negatively buoyant underflow most of year. Wind mixing in shallow littoral regions can significantly enhance the dilution of negatively buoyant spring water with lake water, which may reduce the intrusion depth in the lake (Forrest et al., *in press*).

Next, consider Lake Lagarfljot in Eastern Iceland. The strata in this region are both older and less porous than in the neovolcanic zone discussed earlier. Hence, lake inflows are predominantly surface rivers, as opposed to underground springs. The major inflow to Lake Lagarfljot was historically glacial river Jokulsa i Fljotsdal. After the Karahnjukar hydropower plant became operational in 2007, the lake also receives dammed glacial water from Jokulsa a Dal. In contrast to the steady springs, glacial rivers undergo drastic seasonal variations in flow rate and chemical composition. Figure 2a shows that historical



Icelandic Lakes, Physical Characteristics, Figure 2 Comparison of monthly physical characteristics of glacial river Jokulsa i Fljotsdal and Lake Lagarfljot prior to damming. (a) Suspended sediment concentration (1963–1997), (b) water temperature (2001–2007), and (c) calculated density difference (Andradottir, 2008).

suspended sediment concentrations in Jokulsa i Fljotsdal can reach 400 mg/l during summer high flows (70 m³/s). This is approximately tenfold the 20–50 mg/l suspended sediment concentration within Lake Lagarfljot. In winter, the flow rates and suspended sediment concentrations drop to 7 m³/s and 40 mg/l, respectively (Jonsson et al., 1999; Hardardottir and Thorlaksdottir, 2004). The fine glacial sediment inputs substantially reduce the light penetration in the lake (Adalsteinsson, 1976) and give the lake a distinguished milky gray color (see Figure 3). Originating from a melting ice cap, glacial rivers are often colder than direct runoff and spring fed rivers in summer. Figure 2b shows that glacial river Jokulsa i Fljotsdal historically peaks at 6°C, while Lake Lagarfljot surface waters reach 10°C. The fate of the glacial river inflow is, hence, both determined by the suspended sediment concentration and temperature relative to that of the lake. The combined effect is portrayed on Figure 2c, which shows a strong seasonal cycle, with negatively buoyant sediment-rich underflows in the summer and surface intrusions in the winter.

Ecological implications

Inflows are a major source of oxygen, nutrients and other land borne chemicals to aquatic systems. Their initial fate, determined by the inflow dynamics, can influence lake water quality and ecological functions. The cold submerging groundwater inflows to Lake Thingvallavatn contribute to nutrient deficiency in surface waters in summer. This leads to an abrupt 70% drop in primary production in the water column in a matter of days after the thermocline is developed (Jonasson et al., 1992). Primary production is enhanced again during fall turnover when nutrients

that have been accumulating in the bottom waters are mixed throughout the water column.

Less dense surface inflows, due to either geothermal spring or glacial water, are likely to short-circuit at the lake surface in the absence of wind mixing, limiting renewal of bottom water. As a result, oxygen depletion is known to occur in late winters, especially in shallow Icelandic lakes, such as Lake Myvatn (Einarsson et al., 2004).

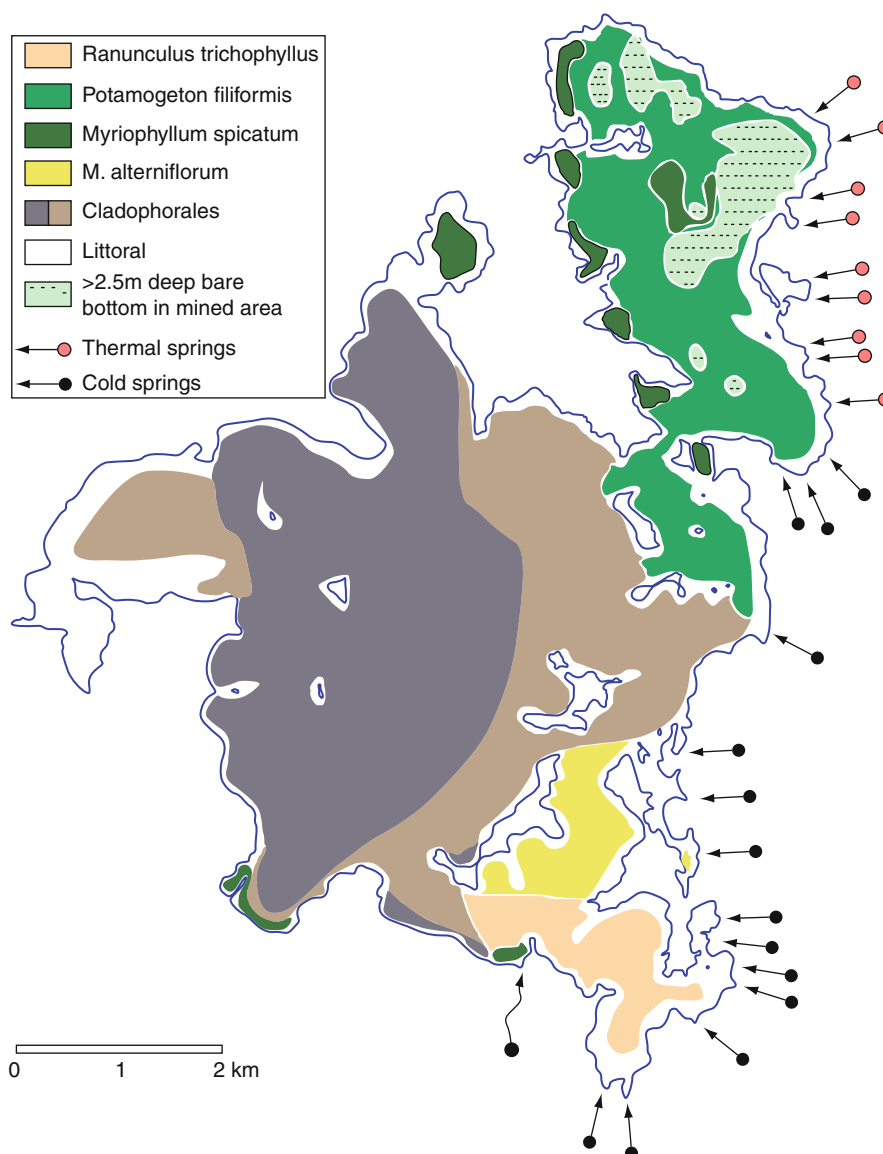
Inflows can also affect spatial variability. For Lake Myvatn, the heterogeneity of groundwater temperature and chemical composition contribute to a range of ecological diversity (Einarsson et al., 2004). Figure 4, for example, shows the difference in macrophyte communities in the north basin of Lake Myvatn, which receives warm spring water; east basin, which receives cold spring water; and south basin, which is disconnected from the east basin through a series of islands.

Water circulation

Lake circulation is governed by the drivers that generate motions and the morphometry which constrains them. First, consider shallow Lake Myvatn. The lake is physically divided into three main basins, as discussed earlier (see Figure 4). During ice cover and/or low winds, water exchanges between lake basins are governed by horizontal density gradients primarily imposed by cold and warm artesian springs and modified by diurnal differential heating and cooling (Palmarsson et al., 2010). The general flow in the south basin is from the inlets in the east toward the outlet in west (Olafsson, 1979). Resuspension of sediments is low, and the nutrient concentrations build up in the sediment pore waters (Einarsson et al., 2004). During ice-free conditions, two wind-induced counterrotating



Icelandic Lakes, Physical Characteristics, Figure 3 Distinctive gray color of Lake Lagarfljot in Eastern Iceland, arising from sediment-rich glacial inflows. (Photo: Hrund Andradottir.)



Icelandic Lakes, Physical Characteristics, Figure 4 Spatial variability of macrophytes in Lake Myvatn in relation to warm and cold groundwater springs. (Modified from Einarsson et al., 2004.)

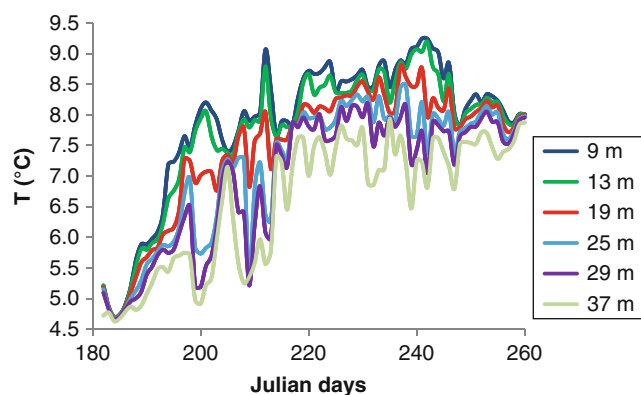
gyres prevail in the south and east basins. The water column is well mixed, validated with observations and depth-averaged hydrodynamical modeling (Kjara et al., 2004; Johannesson, 1991). Wind-driven sediment resuspension and mixing play an important role in releasing nutrients back into the water column, with peaks occurring in spring (Einarsson et al., 2004).

The wind is also the major driving mechanism in weakly stratified deep Icelandic lakes. Results from thermistor chain monitoring in narrow Lake Lagarfljot in summer of 2008, displayed on Figure 5, clearly demonstrate regular oscillations which correspond to basin-scale internal seiches moving along the length of the lake with periods on the order of 1–10 days (Andradottir, 2010).

These slow internal seiches are the key driver for motion, responsible for 5 cm/s near bed velocities along the main lake axis and 3–8 m vertical displacements. The spreading of the temperature time series around Julian day 200 in Figure 5 indicates the presence of vertical modes.

Changing climate and land use

Air temperature increased on average by 0.7°C in the last century in Iceland. Greatest trends were observed in winter temperatures, which increased by 1.2°C over this period (Bjornsson et al., 2008). As water temperature is closely correlated with air temperatures, this warming can have significant winter limnological implications. Ice cover is already observed to be more short lived and



Icelandic Lakes, Physical Characteristics, Figure 5 Filtered water temperatures at different depths in Lake Lagarfljot, July to October 2008. Colors' caption: 9 m (blue), 13 m (green), 19 m (red), 25 m (cyan), 29 m (violet) to 37 m (green) depth (Andradottir, 2010).

intermittent in space and time. Ice cover at Lake Thingvallavatn has been lasting, on average, 5 weeks since 2001, and two winters were completely ice-free (Sveinbjornsson, 2009). This is a drastic change from the 3-month ice cover period historically observed from January to April (Table 2). With shorter duration of ice cover, the likelihood of winter stratification and oxygen depletions is diminished.

While the trend in summer air temperature was insignificant over the last century, a substantial increase has been observed in the past decade. Recent study in shallow Lake Ellidavatn suggests that water temperatures have been increasing in the past 20 years. At the same time, a decline in Arctic charr was observed (Malmquist et al., 2009). New thermistor chain data from Lake Thingvallavatn (Ingimarsson et al., 2011) suggest that deeper lakes may be stratifying for a longer period of time with a stronger gradient (3–4°C) across the thermocline.

With rising air temperatures, Icelandic glaciers have been retreating at a fast rate (Bjornsson et al., 2008). This leads to an increased summer runoff in watersheds dominated by glacial melt, which, in turn, has implications on lakes' residence time, water circulation, and quality. In addition, excessive glacial retreat may alter the flow rate, temperature, and chemical characteristics of groundwater inflows to lakes, such as Lake Thingvallavatn (Palmarsson et al., 2010). Global climate change is also predicted to alter runoff patterns in nonglacial watersheds, with less precipitation falling as snow and more snowmelt in winters (Bjornsson et al., 2008).

Lastly, the damming of glacial rivers alters their temperature, chemical composition, and flow rates (Malmquist, 1998). With the damming of Jokulsa i Dal, glacial water stored in Halslon reservoir is now channelled to Lake Lagarfljot. Results from the first 2 years of this operation suggest that summer suspended sediment concentrations inside the lake have doubled to 100 mg/l

and light transmissivity has halved to 50–60 cm (Adalsteinsson, 2010). This increased suspended sediment concentration within the lake may influence the fate of the inflowing water, reducing the depth and possibly the duration of underflows.

Summary

The physics of subarctic Icelandic lakes differ from those of temperate lakes in several ways. First, the thermal regime is very moderate, and at best, lakes develop a weak (0.1°C/m) and short-lived summer stratification, lasting from June to September. Secondly, many lakes are primarily fed by spring or glacial water, with distinctive physical and chemical properties. Warm groundwater in geothermally active regions enters lakes as surface intrusions, which may contribute to short-circuiting and oxygen depletion, especially during prolonged periods of ice cover. In contrast, cold mineral-rich spring water and sediment-rich glacial river water submerge as they enter lakes, leading to bottom renewal but also nutrient deficiency in the epilimnion. Third, warm and cold artesian springs can coexist in the same lake, driving lateral exchange flows and spatial variability in ecological functions. Fourth, the climate is characterized by strong winds. Shallow systems are often well mixed with depth, where wind resuspension and mixing play an important role in releasing nutrients from the sediments into the water column after prolonged periods of ice cover. The hydraulic regime in deep lakes is characterized by slow wind-driven internal seiches with periods on the order of days. Lastly, global warming is affecting air temperatures, glacial melt, and runoff regimes in Iceland. This, in turn, can have physical, chemical, and biological implications on lake inflows and lake water quality. Shorter periods of lake ice cover are observed, thereby reducing the likelihood of late winter oxygen depletion. There are indications of increasing water temperatures in shallow systems and increased thermal stratification in deeper systems.

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INDIAN LAKES

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Introduction

Being valuable natural resource, lakes have always been of great importance to mankind. From ancient times these have been providing water for domestic use. Since long, lake water is being used for industrial purposes as well as for irrigation. Lake is also one of the means of transport and has always attracted the attention of human beings for

recreation. Some of saline lakes are useful sources of some important minerals as well. In short, a lake is a sort of catalyst in the development of the city, region, and the country as a whole. But, unfortunately, the popularity of lakes often leads to its deterioration. The increased input of industrial and domestic waste and sediments and the human activities not only hamper the capacity of the lake but also cause an increase in the productivity of the lake resulting in the biological and chemical changes leading to hazards like death of fish, obnoxious odor, and unsightly conditions.

A lake is easy to visualize because of its definitive boundary like other types of storage. Lakes are natural reservoirs in which water is temporarily stored during its passage to sea. These receive water as precipitation on their surface, from surface influence and from ground water entering as springs. Lake loses water in the form of evaporation, outflowing streams, contribution to groundwater, etc. Lakes disappear through a process of natural eutrophication involving the nutrients containing sediments. The process of cultural or man-made eutrophication is faster than the natural eutrophication. A distinction between lake and reservoir is that the latter is either a man-made lake or a natural lake augmented with some type of regulation mechanism.

Hydrologic characteristics of lakes vary considerably because of difference in depth, surface area, climate, inflows, and outflows. Lakes may have common features but often exhibit different performance characteristics. Hence, each lake requires its own hydrologic models and these models need to be characterized by different degrees of variance from a generalized conceptual model.

Lakes also exist in all sizes and it is obvious that a small pond of 0.01 km^2 is totally different in most ways than, lake of 50 km^2 . Climate, geology, and anthropogenic influences are other factors that make each lake unique.

Lake has its hydrologic response. It has cause and effect relationship with the adjoining catchment. Because of storage of large mass of water, it moderates flood and climatic factors in the region. Also the deforestation, conversion of grassland to cropland, intensification of agricultural production, land amelioration, etc., in the nearby catchment area affect the microclimate and reduce evapotranspiration thereby increasing runoff and rate of erosion and siltation. Accelerated nutrient cycles and faster transport of soil particles increase rate of sediment deposition and lead to enrichment of stored water. Therefore, various physical, chemical, and biological inputs manifested through the hydrology of the catchment and lake affect the quality and quantity of the stored water.

Lakes of India

Water in rivers and lakes amount to be about 1% of the water budget but its importance to life and human geography is enormous. It is estimated that the world's lakes contain about four times freshwater than its rivers. Lakes are used extensively by people in many countries as the natural centers of civilization. Following the world trend lakes

have been the first priority of available natural resources for development of civilization. In Western India, even during the Maurya period (320 BC) a major reservoir called "Sudarshana lake" was made at the foot of Mount Girnar (Wunderlich et al., 1987). Also the lakes in India have been extensively utilized resulting in overexploitation.

In India, natural and/or man-made changes in storage of lakes, both in quality and quantity of water, have altered not only the stream flow regime but also the water balance of the region. Alteration of flow regime and quality of lake water, a common problem faced everywhere, arising from increase in demand and developmental activities, is resulting in the hampering of activities supported by these lakes. There are also side effects of ecological imbalances in the region. Impact of degradation is less in the initial stage but the cumulative impact in longer period proves to be deleterious. In many cases, if the state of the problems and their remedial measures is not looked into, it would be difficult to save the lakes and therefore, the adjoining area from economical, hydrological, and environmental disasters.

In national perspective, the most important ecological problems connected with lakes are:

1. Lowering of level due to over use of water as a result of decreasing rainfall in the catchment
2. Rapid siltation caused by accelerated soil erosion
3. Pesticides and toxic chemicals being brought through surface water inflow
4. Eutrophication
5. Disintegration of aquatic system

Problems of Indian lakes

During recent years, due to alteration of landscape by denuding forests, urbanization including tourism and waste discharge into the lakes, sedimentation and consequent eutrophication have increased. Even many high-altitude lakes in Kashmir and in Garhwal Himalayas, which have remained clean and without eutrophication for centuries, are showing signs of deterioration. The famous Dal Lake in Kashmir, which was about 40 km^2 in the beginning of nineteenth century, is presently at about 20 km^2 . Almost half of Lake Renuka (water spread of 670 ha), the biggest lake in the Himachal Pradesh in lower Siwaliks of Himalayan region, is filled up with sediment. Upper Lake in Bhopal, Poondi, Red Hills in Madras, and Osmansagar in Hyderabad, sources of drinking water for these cities, have shrunk considerably in the recent past causing hardships. In many cases, lakes of smaller sizes in the urban areas are used for dumping of solid and liquid wastes, due to which the thermal regime of the lake has changed. As a result, smaller lakes in India are experiencing the problem of eutrophication and facing untimely death. Occurrence of inorganic nutrients in water and the resulting increase in vegetative productivity has become a serious water quality consideration in the country.

Indian Lakes, Table 1 Statistics of Indian lakes

Lakes in Northern India

Lake	Dal lake in Srinagar, Jammu and Kashmir
Location	In the heart of city, Srinagar, State – Jammu and Kashmir, India
Location on map	34°07'N 74°52'E
Climate	Arid cold climate. It receives an average annual rainfall of 655 mm (25.8 in.) in the catchment, but during the summer, snow melt from the higher ranges of the catchment results in large inflows into the lake.
Altitude	1,587 m above mean sea level in the flood plain of river Jhelum in the eastern part of Srinagar city at the foot of Zabaravan mountains
Surface area	18–22 km ² (6.9–8.5 miles ²). Max. length 7.44 km (4.62 miles) Max. width 3.5 km (2.2 miles) Average depth 1.42 m (4.7 ft) Max. depth 6 m (20 ft) Water volume 983 MCM Residence time 22.16 days Shore length 15.5 km (9.6 miles) Surface elevation 1,583 m (5,194 ft) Catchment area 316 km ² (122 miles ²)
Inflow	Eighty percent of the inflow to the lake is supplied through the Telbal Nallah and 20% through direct precipitation. The maximum flood discharge of Telbal Nallah has been assessed as 141.5 m ³ /s for a 1 in 100 return period; the 1973 observed flood in Telbal Nallah has been estimated as 113 m ³ /s. The average annual flow, according to discharge measurements, has been estimated as 291.9 million cubic meters (MCM). Spring sources also contribute to the flow, although no specific data is available to quantify their contribution.
Outflow	There are two outlets from the lake, namely, the Dalgate and Amir Khan Nallah that connects the lakes of Nagin and Anchar. Dalgate is controlled by a weir and lock system. The outflow from these two outlets has been estimated as 275.6 MCM. Further, the silt load has been estimated at 80,000 t per year with 70% contribution from the Telbal Nallah, with 36,000 t recorded as settling in the lake. A small canal connects Dal lake with the Anchor lake and acts as an additional outflow channel.
Type of lakes	A natural freshwater lake, Warm monomictic. Frozen during severe winter. There are two islands (Sona Lank and Rupa Lank (or Char Chinari)) in the lake.
Ecological status	The ecosystem of Dal lake is ecologically rich in macrophytes, submerged macrophytes, floating macrophytes, and phytoplankton. Macrophyte flora recorded in the lake's aquatic and marshland environment consists of 117 species, belonging to 69 genera and 42 families. The lake is noted in particular for its <i>Nelumbo nucifera</i> (lotus flowers) which bloom in July and August. The prolific growth of <i>Ceratophyllum demersum</i> in the eutrophic zones has been reported, with <i>Myriophyllum spicatum</i> and <i>Potamogeton lucens</i> cited as dominant species. Other macrophytes discerned in different zones of the lake include <i>Typha angustata</i> , <i>Phragmites australis</i> , <i>Myriophyllum</i> , <i>Sparganium erectum</i> , and <i>Myriophyllum verticillatum</i> , which contribute to the production of macrophytes. The rooted variety of the floating leaf type consists of <i>Nelumbium nucifera</i> , <i>Nymphaea alba</i> , <i>N. Tertagonia</i> , <i>N. Candida</i> , <i>Nymphoides peltatum</i> , <i>Salvinia natans</i> , <i>Hydrocharis dubia</i> , <i>Nymphaea</i> sp., and <i>Potamogeton natans</i> , all of which occupy 29.2% of the lake. Phytoplanktons include <i>Navicula radiosa</i> , <i>Nitzschia acicularis</i> , <i>Fragilaria crotonensis</i> , <i>Diatoma elongatum</i> , <i>Scenedesmus bijuga</i> , <i>Pediastrum duplex</i> , <i>Tetraedron minimum</i> , <i>Microcystis aeruginosa</i> , and <i>Merismopedia elegans</i> . Woody vegetation in the catchment of the lake consists of <i>Melia</i> , <i>Ailanthus</i> , <i>Robinia</i> , <i>Daphne</i> , <i>Celtis</i> , <i>Rose</i> , <i>Ephedra</i> , <i>Pinus roxburghii</i> , <i>Pinus halepensis</i> , <i>Pinus gerardiana</i> , <i>Cupressus torulosa</i> , and <i>Cupressus arizonica</i> . The valley also has a rich cultivation of crops such as paddy, wheat, and fodder.
Changes over the last years	The lake has been extensively reclaimed to form man-made islands separated by canals and areas of water covered by floating gardens. Total water spread area of the lake has shrunk to 12.4 km ² from 23.4 km ² in 120 years. The shrinkage is attributed to heavy siltation and urbanization. Since 1934, some important changes have been observed in the lake's biota, including a reduction in the number of Charaspecies, and an increase in the area covered by <i>Salvinia</i> since 1937. Analysis of the lake has also revealed the tendency for it to develop monospecific communities of submerged macrophytes such as <i>Ceratophyllum</i> and <i>Myriophyllum</i> .
Biodiversity	The lake is shrinking due to deposits of large quantities of silts being dumped into the lake by Telbal Nallah. The faunal distribution consists of Zooplanktons, Benthos, and Fish. Zooplanktons found in the lake include <i>Keratella cochlearis</i> , <i>K. serrulata</i> , <i>Polyactis vulgaris</i> , <i>Brachionus plicatilis</i> , <i>Monostyla bulla</i> , <i>Alona monocantha</i> , <i>Cyclops ladakanus</i> , and <i>Mesocyclops leuckarti</i> . Benthos include <i>Chironomus</i> sp. and <i>Tubifex</i> sp. and fish include <i>Cyprinus carpio specularis</i> (economically important), <i>C. carpio communis</i> , <i>Schizothorax niger</i> , <i>S. esocinus</i> , <i>S. curvifrons</i> , and <i>Crossocheilus latius</i> . It is also reported that <i>Cyprinus</i> , introduced during the early 1960s, is dominant and that the indigenous species of the genus <i>Schizothorax</i> is showing a declining trend.

Indian Lakes, Table 1 (Continued)

Recreation	It is a major center of tourism. Floating gardens, labeled the “Rad” in the Kashmiri language, are a special feature of the lake. They basically constitute of matted vegetation and earth, but are floating. These are detached from the bottom of the lake and drawn to a suitable place (generally to the northwest of the houseboats’ location) and anchored. Given its rich nutrient properties, tomatoes, cucumbers, and melons are grown with noteworthy results.
Commercial use	The fishing industry on Dal lake is the second largest industry in the region and is central to many of the people’s livelihoods who reside on the lake’s periphery. Dal lake’s commercial fisheries are particularly reliant on carp fish species, which were introduced into the lake in 1957. As a result, carp constitutes 70% of all the fish caught in the lake while the <i>Schizothorax</i> constitutes 20% and other species account for 10%. Fishermen use a locally manufactured cast net which comprises six parts with a diameter of 6 m. It is operated from a wooden fishing boat made out of deodar, typically 20 ft × 4 ft in size. The gradual decline in quality of the lake water through pollution has resulted in lower fish stocks and the extinction of endemic varieties of fish. The causes for such deterioration have been identified and remedial actions have been initiated.
Studies undertaken	Considerable study had been carried out on the limnological, ecological, environmental, eutrophication, and siltation problems of the lake. Bathymetric survey was first introduced in 1976 in the lake study for Dal lake. Studies of the water quality of the lake in 1983–1984 indicate a decline in quality since the 1965–1966 analysis. Scientific researches over the years also reveal that Telbal, Botkal, and sewage drains are responsible for a substantial influx of nitrogen and phosphorus into the lake. Quantitatively, 15 drains and several other sources have released a total of 156.62 t (56.36 t by drains alone) of phosphorus, and 241.18 t of inorganic nitrogen into the lake from a discharge of 11.701 MCM/year. Nonpoint sources, such as seepage and diffused runoff, also add to this pollution and have been recorded as further adding 4.5 t of total phosphates and 18.14 t of nitrogen (NO ₃ —N and NH ₄ —N) to the lake. Based on the values mentioned above, it has been inferred that the water quality of the lake has deteriorated. The lake is warm monomictic (mixing type) and the pH value recorded has varied from a minimum of 7.2 to a maximum of 8.8 on the surface over a yearly period. The Dissolved oxygen (mg l ⁻¹) value has varied from a minimum of 1.4 to a maximum of 12.3 on the surface within a year. The recorded maximum nitrogen concentration (NH ₄ -N [micro l—l]) has been recorded as 1,315 on the surface and 22 at the bottom of the lake. Phosphorus concentration expressed in Total-P (micro l—l) has varied from a high of 577 to a low of 35 during the 12 months of the year. The lake water temperature has varied from a minimum of 3°C (37°F) in January to a maximum of 26°C (79°F) in June at the surface. Transparency, expressed as depth in meters, has varied from a maximum of 1.95 m (6.4 ft) in July to a minimum of 0.53 m (1.7 ft) in March, over the 12 months period.
Governing authority General	Dal lake Development Authority, Srinagar, Jammu and Kashmir The major environmental problem facing the lake is eutrophication, which has required immediate remedial measures to combat it. Alarming, the size of the lake has shrunk from its original area of 22 km ² (8.5 miles ²) to the present area of 18 km ² (6.9 miles ²), and there is a concerning rate of sediment deposition due to catchment area degradation. The water quality has also deteriorated due to intense pollution caused by the untreated sewage and solid waste that is fed into the lake from the peripheral areas and from the settlements and houseboats. Encroachments of water channels and consequent clogging have diminished the circulation and inflows into the lake; so with the building up of phosphates and nitrogen, this has led to extensive weed growth and consequences on the biodiversity of the lake.
Lake	Wular lake in Jammu and Kashmir
Location	In Bandipore district of Jammu and Kashmir
Location on map	34 20’N 74 36’E
Climate	The catchment area has a warm, dry summer and cold, wet winter. It receives an average annual rainfall of 700 mm in the catchment, but during the summer, snow melt from the higher ranges of the catchment results in large inflows into the river and the lake.
Altitude	1,580 m above mean sea level in the flood plain of river Jhelum.
Surface area	The lake’s size varies from 12 to 100 miles ² (30–260 km ²), depending on the season. Presently maximum depth of the lake is about 40 m. Maximum depth of lake has reduced to 40 m from about 100 m in the last 200 years.
Inflow	Fed by the Jhelum River.
Outflow	Outflow from the lake again goes to Jhelum River
Type of lakes	Wular lake is a large freshwater natural lake. The lake basin was formed as a result of tectonic activity.
Ecological status	The lake is 1 of 6 Indian wetlands designated as a Ramsa Site. However, it faces environmental threats including the conversion of large parts of the lake’s catchment areas into agricultural land, pollution from fertilizers and animal wastes, hunting of waterfowl and migratory birds, and weed infestation in the lake itself.

Indian Lakes, Table 1 (Continued)

Changes over the last years	In ancient times, Wular lake was also called “Mahapadamsar.” Nilamata Purana also mentions it as “Mahapadmasaras.” Mahapadamsar is referred as Bolor by Al-Biruni (AD 960–1031). The lake, with its big dimensions and the extent of water, gives rise to high leaping waves in the afternoons, called Ullola in Sanskrit, meaning stormy leaping, high rising waves. Therefore, it was also being called “Ullola.” Its corrupted form saw its transition as “Bolor” by Al-Biruni and over the centuries corrupted further to “Wulor” or “Wular.” The origin may also be attributed to a Kashmiri word “Wul,” which means a gap or a fissure, appellation that must have come also during this period. The word Wul (Gap or fissure) is also an indicator of its origin to a fissure or gap created.
Biodiversity	Wular lake is an important fish habitat, the main species being the common carp (<i>Cyprinus carpio</i>), rosy barb (<i>Barbus conchontius</i>), mosquitofish (<i>Gambusia affinis</i>), <i>Nemacheilus</i> species, <i>Crossocheilus latius</i> , and various snowtrout (disambiguation needed) species in the genera <i>Schizopyge</i> and <i>Schizothorax</i> . Snowtrout species identified in the lake include the Sattar snowtrout (<i>Schizopyge curvifrons</i>), Chirruh snowtrout (<i>Schizopyge esocinus</i>), <i>Schizothorax planifrons</i> , <i>Schizothorax macropogon</i> , <i>Schizothorax longipinus</i> , and Chush snowtrout (<i>Schizopyge niger</i>). Fish from Wular lake make up a significant part of the diet for many thousands of people living on its shores and elsewhere in the Kashmir valley. More than 8,000 fishermen earn their livelihood from the lake, primarily fishing for the endemic <i>Schizothorax</i> species and the nonnative carp. Their catch comprises about 60% of the total yield of fish in Kashmir. Hundreds of other local villagers are employed by cooperative societies that trade the fish catch. Many other families harvest plants such as the grass <i>Phragmites</i> and the waterlily-like <i>Nymphoides</i> from the lake for animal fodder. The lake sustains a rich population of birds. Terrestrial birds observed around the lake include the black-eared kite, sparrow hawk (disambiguation needed), short-toed eagle, Himalayan golden eagle, monal pheasant, chukar partridge, koklass pheasant, blue rock pigeon, cuckoo, small cuckoo, alpine swift, Kashmir roller, Himalayan Woodpecker, hoopoe, common swallow, golden oriole, and others.
Recreation	The Kashmiri sultan Zain-ul-Abidin is reputed to have ordered the construction of the artificial island of Zaina Lank in the middle of the lake in 1444.
Commercial use	The Tulbul Project is a “navigation lock-cum-control structure” at the mouth of Wular lake. According to the original Indian plan, the barrage was expected to be of 439-ft long and 40-ft wide, and would have a maximum storage capacity of 0.30 million acre-feet of water. One aim was to regulate the release of water from the natural storage in the lake to maintain a minimum draught of 4.5 ft in the river up to Baramulla during the lean winter months. The project was conceived in the early 1980s and work began in 1984. There has been an ongoing dispute between India and Pakistan over the Tulbul Project since 1987, when Pakistan objected that it violated the 1960 Indus Water Treaty. India stopped work on the project that year, but has since pressed to restart construction. The Jhelum River through the Kashmir valley below Wular lake provides an important means of transport for goods and people. To sustain navigation throughout the year a minimum depth of water is needed. India contends that this makes development of the Tulbul Project permissible under the treaty, while Pakistan maintains that the project is a violation of the treaty. India says suspension of work is harming the interests of people of Jammu and Kashmir and also depriving the people of Pakistan of irrigation and power benefits that may accrue from regulated water releases.
Studies undertaken	Limnological studies
Governing authority	Government of Jammu and Kashmir
Lake	Haigam Rakh in Jammu and Kashmir
Location	Situated at 30 km north west of Srinagar
Location on map	34°15'N 74°31'E
Climate	The summer climate is warm and dry and the winter is cold and wet. The average annual rainfall is 850 mm
Altitude	1,580 m above mean sea level.
Surface area	Water spread area of the lake is 1,400 ha. Maximum depth of water in the lake is 1.25 m.
Inflow	From the catchment area
Outflow	There is no outflow from the lake.
Type of lakes	A small freshwater lake on the flood plains of Jhelum.
Ecological status	The rate of siltation and eutrophication in the lake are high. The lake is covered with dense red weed.
Changes over the last years	Lake is shrinking due to siltation from all around the lake.
Commercial use	For tourism purpose.

Indian Lakes, Table 1 (Continued)

Studies undertaken	Limnological and biological study. Study on mineral composition, bio-geochemical cycling, plankton population, biomass productivity, trophic structure, and plant community architectures. The Bombay Natural Society had worked on flora and fauna of the lake. The Department of Wild Life Protection had conducted some waterfowl census and two Oxford University Expeditions had studied the breeding birds and passage migrants.
Governing authority	Government of Jammu and Kashmir
Lake	Mansar lake, Jammu and Kashmir
Location	62 km (36 miles) from Jammu
Location on map	34°14'–35°01'N ; 74°40'–74°43'E
Climate	The summer climate is warm and dry and the winter is cold and wet. The average annual rainfall is 800 mm
Altitude	2,000 m above mean sea level.
Surface area	Over a mile in length by half-a-mile in width.
Inflow	From the catchment area
Outflow	Through underground channels
Type of lakes	Mansar is a beautiful lake fringed by forest-covered hills
Ecological status	The lake is still fresh but showing sign of eutrophication.
Changes over the last years	The lake is shrinking due to boulders being brought by snow melt. The tourists visiting the lake spill waste around the lake due to which it is getting polluted.
Biodiversity	With all religions' belief and heritage behind, the Mansar lake is also picking up its fame among the tourists with all its flora and fauna. The lake has cemented path all around with required illumination, with projected view decks to enjoy flickering of seasonal birds, tortoise, and fishes of different species. There is a wild life sanctuary housing jungle life like Spotted Deer, Neelgai, etc., besides other water birds such as Cranes, Ducks, etc. One can also witness the traditional and typical distinct life style of Gujjar and Backarwals wearing ethnic costume, living in open Kullhas around on the hills of Mansar lake.
Recreation	Besides being a popular excursion destination in Jammu, it is also a holy site, sharing the legend and sanctity of lake Mansarovar. On the Eastern Bank of the lake there is a shrine to Sheshnag, a mythological snake with six heads. The shrine comprises a big boulder on which are placed a number of iron chains perhaps representing the small serpents waiting on the tutelary deity of the Sheshnag. Two ancient temples of Umapati Mahadev and Narsimha and also a temple of Durga are situated in the vicinity of the Mansar lake. People take a holy dip in the water of the lake on festive occasions.
Commercial use	Newly weds consider it auspicious to perform three circum-ambulations (Parikarma) around the lake to seek the blessings of Sheshnag, the Lord of serpents, whose shrine is located on its eastern bank. Certain communities of Hindus perform the Mundan ceremony (First hair cut) of their male children here. There are also some ancient temples on the lake's shores, which are visited by devotees in large numbers. Mansar is also ideal for boating for which the Tourism Department provides adequate facilities. This Mansar lake road joins to another important road that directly links Pathankot (Punjab) to Udhampur (Jammu and Kashmir, Jammu Province). Udhampur is a town of strategic importance, again on National Highway No. 1A.
Studies undertaken	Hydrological studies have been undertaken by National Institute of Hydrology, Roorkee.
Governing authority	Government of Jammu and Kashmir, India
Lake	Nainital lake in Uttarakhand (Erstwhile Uttaranchal)
Location	In the heart of Nainital in Uttarakhand State of India
Location on map	29°24'N 79°28'E/29.4°N 79.47°E
Climate	The annual rainfall in the basin area of the lake is 1,294.5 mm (43.15 in.). Tropical monsoon climate with maximum temperature 24.6°C and minimum of 0.5°C.
Altitude	1,937 m above mean sea level
Surface area	The lake area is about 5.85 km ² . The areal extent of the lake is also reducing. Maximum depth of lake has reduced from 27.45 m in 1950 to about 24 m in 1980. Max. length 1,432 m (4,698 ft) Max. width 42 m (138 ft) Surface area 48.76 ha (120.5 acres) Max. depth 27.3 m (90 ft) Residence time 1.16 years Surface elevation 1,938 m (6,358 ft)
Inflow	The lake receives flows from the surrounding catchment basin which comprises the hill slopes and springs.
Outflow	Has an outfall at the south-eastern end. The components of outflows were the surface outflow, the subsurface outflow through the springs on the downstream side and draft through wells for meeting the water supply of Nainital town and evaporation loss from the lake surface.

Indian Lakes, Table 1 (Continued)

Type of lakes	A freshwater lake. There is a submerged island running across center of the lake dividing it into two basins. Tectonic in origin, is kidney shaped or crescent shaped.
Ecological status	The lake is bounded by the high and steep Naina peak on the northwest side, by the Tiffin Top to the southwest side and snow view peaks on the north. Coniferous forest trees cover these hill ranges.
Changes over the last years	Deforestation of the surrounding hills is causing landslide due to which heavy load of boulders and sediment get dumped in the lake from time to time. Lake capacity is reducing
Biodiversity	The Nainital district, where the lake is situated (in the middle Himalayan ranges up to 2,000 m (6,600 ft), a temperate zone), is rich in flora (typical temperate climate plants) and fauna. Vegetation: The trees and bushes grown in the region (lake's basin) with their botanical and common Indian names (in parenthesis) are reported to be: (a) <i>Quercus incana</i> (Oak [Banj]); (b) <i>Aesculus indica</i> (Pangar or Horse chestnuts); (c) <i>Juglans regia</i> (Akhrot or walnut); (d) <i>Populus ciliata</i> (Hill Pipal, a sacred tree); (e) <i>Fraxinus micrantha</i> (Ash tree or Angu); (f) <i>Platanus orientalis</i> (Chinar); (g) <i>Rubus lasiocarpus</i> (Himalu); (h) <i>Rosa moschata</i> (Kunj or Musk rose); (i) <i>Berberis asiatica</i> (Kilmora); (j) <i>Cupressus torulosa</i> (Surai or Himalayan cypress); (k) <i>Rhododendron arboreum</i> (Buruns), <i>Cedrus deodara</i> (Deodar); (l) <i>Salix acmophylla</i> (Weeping Willow); and (m) <i>Pinus</i> (Pine). The aquatic macrophytic vegetations recorded are (1) <i>Potamogeton pectinatus</i>, (2) <i>Potamogeton crispus</i>, (3) <i>Polygonum glabrum</i>, (4) <i>Polygonum amphibium</i>, and (5) <i>Polygonum hydropiper</i> (Water pepper). Several species of medicinal flora and horticulture plants have also been reported. Aqua fauna: The fishes found in the lake are generally carps mahseer, (the Hindi name of mahāsir, mahāser, or mahāsaulā used for a number of fishes of the group), also hill trout and the mirror carp which breed several times during one spawning season during May to September. Two species of Mahaseer fish, viz., <i>Tor tor</i>: The red finned mahseer and the <i>Tor putitora</i>: The yellow finned mahseer, a food fish which grows to varying sizes from 20 to 60 cm (7.87–23.62 in.) are reported. The three species of hill trout found in the lake are the <i>Schizothorax sinuatus</i>, <i>Schizothorax richardsoni</i>, and <i>Schizothorax plagiostomus</i>. The imported fish bred in the lake is Mirror carp or <i>Cyprinus carpio</i>. <i>Gambusia affinis</i> also called Mosquitofish have been introduced in the lake as a biocontrol measure to control mosquito larvae. Fauna: Nine species of birds and nine species of animals have been recorded in the Nainital district.
Recreation	There is the Nainital Boat Club that offers yachting facilities at the lake. The Annual Kingfisher Yachting Competition (Regatta) is held here in the third week of June. The Kumaun Festival, exhibiting local cultures and traditions, is organized by the Tourism Department every year during the winter months of October and November.
Commercial use	The lake is the epicenter of tourism in Uttarakhand.
Studies undertaken	Several limnological and hydrological studies have been undertaken. The water is reported to be alkaline in nature (ph value of 8.4–9.3). The hydrologic studies related to water balance and sedimentation were done using radioisotopes for estimating/measuring the various components of the inflow and outflow into the lake. Studies indicated that the subsurface inflow and outflow were significant – ranging from 43% to 63% and 41% to 54%, respectively, of the total inflow and outflow, except in years of exceptionally heavy rainfall. The mean water retention time for the lake was computed as 1.16 years for the mean annual rainfall. A scientific study indicates that the open drains feeding the lake introduce toxic substances from the catchment of the lake, particularly heavy metals which get adsorbed onto the suspended sediments, which in turn settle down in the bottom of the lake. A study of the risk assessment code has revealed that 4–13% of manganese, 4–8% of copper, 17–24% of nickel, 3–5% of chromium, 13–26% of lead, 14–23% of cadmium, and 2–3% of zinc exist in exchangeable fraction which puts the lake under the low-to-medium risk category and infers that it could enter into food chain and also cause deleterious effects to aquatic life. This study provides the basic database to formulate guidelines for the dredging operations and/or restoration programs in the lake. The water quality studies carried out by the National Institute of Hydrology during 1999–2001 on physicochemical parameters (pH, temperature profile, Secchi's transparency, dissolved oxygen, BOD, COD, and nutrients), biological profile (density of population, biomass and species diversity of phyto, zooplankton and macrobenthos), and bacteriological characteristics have led to the conclusion that long-term limnological changes have occurred in the lake. Excess of nutrients inflow have contributed to the eutrophic conditions and the internal recycling of nutrients from sediments during water circulation has resulted in luxurious growth of phytoplankton. The lake is thus anoxic and has reduced hypolimnion, winter circulation, large phytoplankton, and relatively lower animal population.

Indian Lakes, Table 1 (Continued)

Governing authority
General

Nainital Lake Development Authority

Lake Restoration

The National Institute of Hydrology (NIH) of Roorkee, India, who prepared a plan for the restoration of the lake, at an estimated cost of Rs. 50 crore (about US\$10 million), sponsored by the Ministry of Environment and Forests, Government of India, is also now guiding the restoration measures. The Conservation and Management Plan evolved by NIH is not only lake centric but also proposes to tackle the immediate periphery of the lake which contributes an adverse impact on the lake. The "Nainital Jheel Parikshetra Vishesh Kshetra Vikas Pradhikaran," the Lake Development Authority notified under U.P. Special Area Development Act 1986 is a Special Purpose Vehicle (SPV) set up for implementing the restoration works. The restoration works that have been implemented or are in different stages of implementation are the following:

Limnological measures such as controlled aeration of hypolimnetic water, siphoning of hypolimnetic water, biomanipulation and limited sediment removal from the deltas of drains which lead to the lake.

Soil Conservation and Slope Stabilization measures in the form of soil conservation and watershed management activities in the catchment area of the lake, slope stabilization, Drainage line treatment, landslide scars to be treated with Coir geotextiles with gabion cross-barriers and proper maintenance and cleaning of drainage system.

Provide 100% coverage of the town surrounding the lake with sewers and Sewage Treatment Plants (STPs).

Improved sanitation around the lake and in the catchment with new community toilets to cover all sections of the society, improved design of household toilets.

Better solid waste management by disposing solid waste through a chute to the downhill outside the catchment, developing landfill sites in isolated habitations in the upper reaches of hills, and introducing composting measures with support from NGOs.

Limited dredging of the lake, particularly near the deltas of drains that bring sediments.

Fish *Gambusia affinis* introduced a few years ago to control mosquito larvae, the fish have started feeding on the larger zooplankton resulting due to scanty larvae population resulting in adverse impact on the lake water quality. This needs to be controlled by putting minnow traps in the lake and introducing some other fish species.

The outflow from the lake is into the Balia Nala drain controlled by a set of sluices located at the lake bridge. The sluices which are old need renovation and replacement. The Balia Nala also needs slope stabilization measures to check landslides.

Shoreline Development and improvement of facilities at all important monuments and temples located in the periphery of the lake and providing avenue paths and roads.

Improved public awareness and public participation programs.

The "Nainital Jheel Parikshetra Vishesh Kshetra Vikas Pradhikaran" could function better in a limited role as a promoter and a facilitator for developmental and commercial activities with jurisdiction extended to cover all four lakes in the district, as at present a plethora of organizations are functioning in the notified area such as Nainital Nagar Palika Parishad, Jal Nigam, Irrigation Department, Power Corporation, Forest Department, and Fisheries Department who are directly involved with the lake.

The Honorable Supreme Court of India in its judgment of 1995, in response to the Public Interest Litigation, gave the following recommendations which have also been addressed in the restoration measures mentioned above.

- (1) Sewage water has to be prevented at any cost from entering the lake; (2) So far as the drains which ultimately fall in the lake are concerned, it has to be seen that building materials are not allowed to be heaped on the drains to prevent siltation of the lake; (3) Care has been taken to see that horse dung does not reach the lake. If for this purpose the horse stable has to be shifted somewhere, the same would be done. The authorities would examine whether trotting of horses around the lake is also required to be prevented; (4) Multi-storied group housing and commercial complexes have to be banned in the town area of Naini Tal. Building of small residential houses on flat areas could, however, be permitted; (5) The offence of illegal felling of trees is required to be made cognizable; (6) Vehicular traffic on the Mall has to be reduced. Heavy vehicles may not be permitted to ply on Mall; and (7) The fragile nature of Ballia Ravine has to be taken care of. The cracks in the revetment of Ballia Nullah have to be repaired urgently.

In his article, "Lady of the Lake" in *India Today* (India Today, 2001), S. Prasannarajan, a journalist, has very vividly described the lake in these words in a preamble to the particular interest shown by Aradhana Shukla, The Lady District Magistrate of Nainital in restoration works of the lake:

Look for the lake through the colonial windows of Pant House, a vintage English bungalow on the hilltop, now submerged in wintry night, solitary with a kind of Wuthering Heights mystery. Down below, the lake is a laminated stillness, protected by seven never-sleeping hills. In the dead darkness of Kumaon, this magnificence is a distant, partially lit vision, less than real, as the hills of frozen memories make the lake a footnote in water.

Indian Lakes, Table 1 (Continued)

Lake	Naukuchiatal lake in Uttarakhand
Location	Situated at a distance of 5 km from Bhimtal lake in Nainital district of Uttarakhand.
Location on map	29°32'N 79°21'E.
Climate	The annual rainfall in the basin area of the lake is 1,200 mm. Tropical monsoon climate with maximum temperature 24.6°C and minimum of 0.5°C.
Altitude	1,320 m above mean sea level.
Surface area	It has an irregular shape. The maximum aerial extent of the lake is 90 ha. Lake basin is a conical deep trough with flat bottom. Basin walls have steep slope. Mean depth of the lake is about 21.89 m. Maximum depth of the lake is 41.25 m.
Inflow	From Nainital lake
Outflow	It has a small artificial outlet leading to Bhimtal Gadhera
Type of lakes	Naukuchiatal lake is the deepest and most voluminous of the Kumaun lakes of the lesser Himalayas.
Ecological status	North west corner of the lake is a delatic plain which is marshy and swampy. To the north west of the lake is the Nal-Damayanti lake which was previously a lake, is now in the form of a tank.
Changes over the last years	The lake is facing a threat not only to the quality of its water but to its mere existence too, from the rapid growth of the human activities, not only in catchment area but even in basin area of the lake.
Biodiversity	Vegetation: The trees and bushes grown in the region (lake's basin) with their botanical and common Indian names (in parenthesis) are reported to be: (a) <i>Quercus incana</i> (Oak [Banj]); (b) <i>Aesculus indica</i> (Pangar or Horse chestnuts); (c) <i>Juglans regia</i> (Akhrot or walnut); (d) <i>Populus ciliata</i> (Hill Pipal, a sacred tree); (e) <i>Fraxinus micrantha</i> (Ash tree or Angu); (f) <i>Platanus orientalis</i> (Chinar); (g) <i>Rubus lasiocarpus</i> (Hisalu); (h) <i>Rosa moschata</i> (Kunj or Musk rose); (i) <i>Berberis asiatica</i> (Kilmora); (j) <i>Cupressus torulosa</i> (Surai or Himalayan cypress); (k) <i>Rhododendron arboreum</i> (Buruns), <i>Cedrus deodara</i> (Deodar); (l) <i>Salix acmophylla</i> (Weeping Willow); and (m) <i>Pinus</i> (Pine). Several species of medicinal flora and horticulture plants have also been reported. Aqua fauna: The fishes found in the lake are generally carps mahseer, (the Hindi name of mahāsir, mahāser, or mahāsaulā used for a number of fishes of the group), also hill trout and the mirror carp which breed several times during one spawning season during May to September. Two species of Mahaseer fish, viz., Tor tor: The red finned mahseer and the Tor putitora: The yellow finned mahseer, a food fish which grows to varying sizes from 20 to 60 cm (7.87–23.62 in.) are reported. The three species of Hill Trout found in the lake are the <i>Schizothorax sinuatus</i> , <i>Schizothorax richardsoni</i> , and <i>Schizothorax plagiotormus</i> . The imported fish bred in the lake is Mirror carp or <i>Cyprinus carpio</i> . <i>Gambusia affinis</i> also called Mosquitofish have been introduced in the lake as a biocontrol measure to control Mosquito larvae. Fauna: Nine species of birds and nine species of animals have been recorded in the Nainital district.
Recreation	For tourism
Commercial use	The lake water is excessively used for irrigation and drinking purposes in the lower valley villages.
Studies undertaken	Considerable studies on limnological and ecological aspects of the lake in Kumaun Himalaya. Limnological study was conducted through bathymetric map.
Governing authority	There is no governing authority.
Lake	Bhimtal lake in Uttarakhand
Location	A lake in the town of Bhimtal, Uttarakhand, India.
Location on map	29°20'35"N 79°33'33"E
Climate	The annual rainfall in the basin area of the lake is 1,294.5 mm (43.15 in.). Tropical monsoon climate with maximum temperature 24.6°C and minimum of 0.5°C
Altitude	1,345 m above mean sea level
Surface area	The maximum depth of the lake is 24.75 m and the minimum depth is 12–13 m. The shoreline index is 1.67 and its development index is 1.74. The total volume of the lake is $4,245 \times 10^3 \text{ m}^3$.
Inflow	From the hilly catchment and underground spring
Outflow	There is no outflow from the lake
Type of lakes	The largest among Kumaun lakes. It is a perennial freshwater lake, irregular in shape.
Ecological status	Over the years, the lake has got filled with debris from all over the catchment and infested with planktons
Changes over the last years	The town though ancient was never prominent because of nearby Nainital which was the summer capital of erstwhile United Province of India and contained all the amenities to be found in any European town. But, over time Nainital became crowded and ugly and the lake so polluted that people do not drink directly from it.
Biodiversity	It is a perennial lake which not only supports a large variety of aquatic life but is also a winter stopover for Trans-Himalayan birds.

Indian Lakes, Table 1 (Continued)

Recreation	It is still center of tourism for the district of Kumaun of Uttarakhand.
Commercial use	For tourism
Studies undertaken	Considerable studies on limnological and ecological aspects of the lake in Kumaun Himalaya. Limnological study was conducted through bathymetric map.
Governing authority	State Government of Uttarakhand.
Lake	Renuka lake in Himachal Pradesh
Location	173 km south west of Shimla, in Sirmur district of Himachal Pradesh, India
Location on map	30°36'36"N 77°27'30"E
Climate	Subtropical monsoon climate. Average annual rainfall in catchment area of the lake is 1,500 mm.
Altitude	700 m above mean sea level
Surface area	Catchment area of 254.3 km ² is in hilly forested terrain. It is the largest lake in Himachal Pradesh, with a circumference of about 3,214 m.
Inflow	The lake is fed by monsoon runoff from the catchment area and perennial underground seepage water.
Outflow	There is no outflow from the lake.
Type of lakes	A natural, low-altitude freshwater lake. It is a long, narrow, oblong-shaped lake flanked by two parallel steep hills running east–west.
Ecological status	A total catchment area of 90% is under the subtropical deciduous reserve forest cover. The lake is threatened by continuously shrinking size. The silt which gets deposited in the lake is causing a major concern to the locals and the administration. The main cause of this is the soil being deposited on the banks, with the rainwater and land slides in the nearby mountains. Also the waste of construction material is being dumped into the lake for years, which is a big threat to the environment. Administration and Renuka Vikas Smiti is trying its best to protect the lake. The plastic bags are banned in the entire region.
Changes over the last years	If corrective measures are not taken to save the lake in a timely manner, it will effect environment and also the business of the locals, which depends upon the Tourism, attracted by the lake. The most loving and important thing is the behavior of small children in that local area; they are quietly adjoining their hands and saying “Namaste” (giving respect and making welcome) to any newer person and tourist. Presently length of the lake is about 1.5 km, breadth is about 0.3 km, maximum depth of water in the lake is about 10.0 m, and minimum depth of water in the lake is about 5.0 m. The lake is fast shrinking. Maximum depth is presently only 10 m which was up to 25 m in the last decade.
Biodiversity	• The lake is monolithic with distinct stratification during May–October. Overturning of lake water takes place. • One fourth of the lake area is covered by marshes. • Freshwater fish habitat used to be in abundance is now decreasing.
	<i>Renuka Sanctuary</i>
	The sanctuary is situated in Sirmour district in Himachal Pradesh. The sanctuary is well connected by the network of motorable roads. The total area of the sanctuary is about 4.028 km ² . The entire sanctuary consists of Renuka Reserve Forest and has been declared as Abhayaranya. An area of roughly about 3 km ² that lies outside the sanctuary has been declared as a buffer belt. The sanctuary falls in the biogeographical zone IV and biogeographical province IV as per the classification done by the Wildlife Institute of India (WII). According to the classification of the types of forest, the area falls under group 5B/C2, i.e., dry mixed deciduous forest, and group 5/051, i.e., dry sal forest.
Recreation	It is the site of an annual fair held in November.
Commercial use	For tourism
Studies undertaken	Limnological and ecological studies with special reference to its flora and fauna.
Governing authority	Himachal Pradesh State Government
General	Lake was named after the goddess Renuka. It is well connected by the road. Boating is available on the lake.
Lake	Maharana Pratap Sagar in Himachal Pradesh
Location	In Kangra district, Himachal Pradesh
	The closest railway stations to the project are Mukerian 30 km (18.6 miles) and Pathankot 32 km (19.9 miles). Nagrota Surian and Jawali located on the periphery of the reservoir are connected by the narrow gauge railway line, the Kangra railway line, which connects Pathankot to Jogindernagar.
Location on map	32°01'N & 76°05'E
Climate	Subtropical monsoon climate. Average annual rainfall in the catchment area of the lake is 1,500 mm.

Indian Lakes, Table 1 (Continued)

Altitude	Low-altitude reservoir
Surface area	Catchment area of 12,561 km ² . Surface area of the lake varies from 240 to 450 km ² . Maximum length is 42 km and maximum width is 2 km. The reservoir is bounded by the rugged Dhauladhar mountain range, the low foothills of the Himalayas on the northern edge of the Indo-Gangetic plains, and the mountain streams cutting through valleys.
Type of lakes	Named in the honor of the patriot Maharana Pratap (1572–1597), the reservoir or the lake is a well-known wildlife sanctuary and one of the 25 wetland sites declared in India by the Ramsar Convention (Belsare et al., 1990; Cavazza, 1993).
Ecological status	Named in the honor of the patriot Maharana Pratap (1572–1597), the reservoir or the lake is a well-known wildlife sanctuary and one of the 25 wetland sites declared in India by the Ramsar Convention. Pong Dam lake was declared a Ramsar Wetland site on account of its rich waterfowl diversity for conservation and sustainable use of the wetland. This recognition was based on a proposal formulated by the Himachal State Council for Science, Technology and Environment, Shimla, submitted to the Ramsar Bureau, Switzerland through the Union Ministry of Environment and Forests of the Government of India. The large reservoir and its strategic location in the extreme northwest of the northern plains has attracted migratory birds from the plains of India and Central Asian countries and Siberia; more than 220 bird species of 54 families were recorded. The interception of the migratory birds on their trans-Himalayan fly path, during each migration season, has enriched the biodiversity values of the reservoir. The Pando reservoir and its catchment have the following rich flora and fauna.
Biodiversity	The reservoir peripheral land area has mixed perennial and deciduous pine forests on hills. Eucalyptus trees have also been grown in the area. The forest growth provides enough sustenance to the migratory birds. The tree species of the forest area are Acacia, Jamun, Shisham, Mango, Mulberry, Ficus, Kachanar, Amla, and Prunus. A variety of shrubs, grasses, and climbers are also reported. The reservoir seasonal water level variation between the maximum water level and the minimum draw down level does not permit growth of much emergent vegetation but some amount of submerged vegetation is noticed A wide variety of commercially viable fish, 27 species of five families, such as Mahseer, <i>Catla</i> , Mirror Carps, Singhara (native), and others are recorded in the Pong Dam reservoir and its tributaries. Before the reservoir was built, catfishes, mirror carps, and a few coarse fish were the dominant fish fauna in the Beas River. With the emergence of the reservoir, commercial fishing was encouraged as an important program not only to provide employment to about 1,500 fishermen but also to promote the ecotourism potential. A planned operation of fish stocking was launched with first introduction of Common carp in 1974 and Indian major carps or Silver carp in 1976–1977. This resulted in a shift in the catch structure of the reservoir with carps accounting for 61.8% of the total landings in 1987–1988. The present fish stocks in the reservoir, in the sequence of their abundance are: (1) Rohu, <i>Aorichthys seenghala</i> , (2) Labeo calbasu (native), (3) <i>Tor putitora</i> (Himalayan Mahseer), (4) <i>Cirrhinus mrigala</i> , (5) <i>Wallago attu</i> , (6) <i>Cyprinus carpio</i> , (7) Labeo dero, (8) <i>Catla catla</i> , and (9) <i>Channa</i> sp. (MAPCOST Report, 1996). The reservoir, unlike other reservoirs in the region, has shown a marked growth in catch of Mahseer fish recording 20% of the total catch during 1999–2000 with the average size of the fish ranging from 1.5 to 1.7 kg (3.3–3.7 lb). This is attributed to the change in the Himachal Pradesh (HP) Fishing Rules with an added clause which specifies the minimum catchable size for Mahseer as 300–500 mm or approximately 1.2 kg (2.6 lb) which is stated to give to each female Mahseer to breed at least once before being caught. Mahseer angling in the Pong Dam reservoir is said to be the only one of its kind in the country. The reservoir was declared as a bird sanctuary in 1983. A 5 km (3.1 miles) belt from the periphery of the lake has been declared as buffer zone for the management of the bird sanctuary. The national as well as international significance of the sanctuary is enhanced because of its waterfowl diversity, which was evidenced by the increase of waterfowl species from 39 prior to the reservoir to 54 species at post-reservoir stage. The number of birds reported, particularly during the winter period of November to March, has steadily increased over the years and the recent records indicate a waterfowl count of 130,000 in 2004 and 142,000 during 2005 migratory birds – a phenomenal increase from the average annual count of 18,887 for the period 1988–1995. The main bird species reported are the barheaded geese (Goose), Anser indicus, northern lapwing (<i>Vanellus vanellus</i>), ruddy shelduck (<i>Tadorna ferruginea</i>), Northern pintail (<i>Anas acuta</i>), common teal (<i>Anas crecca</i>), Mariana Mallard (<i>Anas poecilorhyncha oustaleti</i>), Eurasian Coot <i>Fulica atra</i> , red-necked Grebe (<i>Podiceps griseigena</i>), Black-headed gulls, plovers, Black Stork, terns, waterfowl, and egrets.

Indian Lakes, Table 1 (Continued)

	The avian habitats in the reservoir area are categorized under the following heads: 1. The receding shoreline forms mudflats and mud spits from October onward which provide organic matter, worms, insects, and molluscs for wintering birds and plovers. Wagtails, Sand Larks, and Pipits also use the mudflats. 2. The shallow water on the margins of the reservoir and the open deep water are used by dabbling ducks (Anatinae) and some long-legged waders. 3. In the sandy banks near the reservoir periphery with dry sand banks strewn with small boulders, with little or no vegetation, stone curlew and pratincoles feed here. 4. Below the outfall of the dam, swamp habitats and water side vegetation are used by birds such as ducks, coot, warblers, babblers, munias, kingfishers, and predators. 5. In the reservoir draw down areas, which are also cultivated by local people during winter, bar-headed geese and ruddy shelduck feed. Around 5,000 tourists visit the bird sanctuary during winter season and most of them come to watch migratory birds for the first time. Efforts are being made to encourage ecotourism to attract more tourists to the reservoir. The periphery above the water surface area of the reservoir has recorded fauna species such as barking deer, sambar, wild boars, leopards, and Oriental Small-clawed Otters.
Recreation	Water sports A regional water sports center has been established in the Pong dam reservoir which offers focused activities such as canoeing, rowing, sailing, and water skiing, apart from swimming. Training programs are organized in water safety and rescue measures with three tier water sports courses – the basic course, intermediate course, and advanced course. Modern infrastructure facilities have been created with a 75-bed hostel and a 10-suit rest house. It is said to be the only center of its type in the country.
Studies undertaken	The following protection measures have enabled preservation of the reservoir ecosystem. • Declaring the entire reservoir as a Wildlife Sanctuary in 1986 by the Himachal Pradesh government has mostly eliminated poaching. Forty Village Forest Development Committees are functioning to prevent poaching of birds, in addition to nine check posts. Two mobile check posts monitor suspicious activities in the sanctuary areas in coordination with the established check posts. This vigilance program has established Nagrota Surian, Guglara, Tairess, Jambal Bassi, Nandpur Bhatoli, and Dehra as dwelling places for the migratory birds. • To check siltation of the reservoir and to provide bird nesting places, plantation of the peripheral area of the lake has been undertaken in a large way. • The Protected Area Management Plan envisages boundary protection, habitat improvement, tourism and regulation, roads and staff quarters, and so forth. • One of the islands in the reservoir has been named Ramsar (after the Ramsar Convention) and developed for nature conservation education, complete with rest house and boating facility. • Organized reservoir fishing with full support of the Department of Fisheries has provided opportunities to reservoir Oustee (project affected people due to submergence) families to take up fishing as a profession. As per the last report, more than 1,789 fishermen are engaged in fishing activities which generate secondary benefits to more than 1,000 families. A large number of Fishermen Cooperative Societies are functioning in the reservoir.
General	Maharana Pratap Sagar, also known as Pong Dam Reservoir or Pong Dam lake, was created in 1975 building the highest earth fill dams in India on the Beas River in the wetland zone of the Siwalik Hills of the Kangara district of the state of Himachal Pradesh in India.
Lake	Prashar lake, Himachal Pradesh
Location	49 km north of Mandi in Mandi District
Location on map	32°41'N & 76°55'E
Climate	Subtropical monsoon climate. Average annual rainfall in catchment area of the lake is 1,800 mm.
Altitude	2,730 m above mean sea level
Inflow	Rainwater, Glacial runoff
Outflow	Evaporation
Type of lakes	Holomictic
Ecological status	With deep blue waters, the lake is held sacred to the sage Prashar and he is regarded to have meditated there. Surrounded by snow-capped peaks and looking down on the fast flowing river Beas, the lake can be approached via Drang.
Biodiversity	The lake has a floating island in it and it is said to be unclear how deep it is, with a diver not being able to determine its depth.
Recreation	Prashar lake is also a symbol of natural beauty which is overlooked by snow-draped peaks and is situated on the highest place of Mandi district. This lake is fed by small mountain streams. From the edge of Prashar lake, tourist can see a slice of the distant snow capped peaks. The water of Sutlej river flowing toward south is also visible. On some special occasions, the neighborhood of this lake doubles as the site for certain festivals too.

Indian Lakes, Table 1 (Continued)

Commercial use	The people of the adjoining area throng this temple during an annual fair held here in the month of June and the village deities of this vast mountainous area are carried to this heavenly spot to pay obeisance to sage Prashar.
Governing authority	Bansen, the king of Mandi, got this temple built in the thirteenth century and the temple is in Pagoda style.
General	With a three-storied pagoda-like temple dedicated to the sage Prashar, it is a center of religious ceremony. The temple was built in the thirteenth century and legend has that it was built by a baby using only a single tree. The whole of the temple is built of a single deodar tree.
Lake	Suraj Tal, Himachal Pradesh
Location	In Lahaul Valley, Himachal Pradesh. Suraj Tal is 65 km from Keylong, the district headquarters of the Lahaul-Spiti district, a frontier district of India which is approachable by road by the National Highway NH 21, also known as the Leh-Manali Highway. The NH 21 is the vital road link for the people living in the Lahaul-Spiti district. The road skirts the Suraj Tal and is just 3 km short of the Bara-lacha-la pass. It remains inaccessible from Rohtang Pass to Leh during winter months of November to April since the pass becomes totally snowbound during this period. “During winters it remains in the grip of a pall of ice untidy with lumps of frozen snow and jutting stones.” But in the summer season this tarn comes back to its glorious charm, the deep blue of its icy waters reflecting craggy mountains and snowy heights.
Location on map	The lake is situated in the Upper Himalayan Zone or High Latitudinal Zone part of the Himalayas which has very sparse population with climatic conditions akin to polar conditions. Snowfall in this zone, though scanty, is reported to be spread all round the year. Rainfall precipitation is rare in the region.
Climate	32°45'N 77°24'E to 32.75°N77°54'E Since the lake is in the valley situated in rain shadow area, north of the Pir Panjal ranges of the Himalayas, the weather remains pleasant and quite comfortable during summers, i.e., from May to mid-October. This is the best season to visit this valley. It seldom rains, and the Mercury level does not exceed 30°C and never falls below 15°C throughout the summer season. One can always enjoy bright sunshine wandering within lush green valley. There is little or no rain in monsoons. The climate remains dry and invigorating. The days are hot and nights are extremely cold. Heavy/Light woollens are recommended. During winter, i.e., from the end of November to April because of western disturbances it snows heavily and the temperature goes down below minus. There is an average annual snowfall of about 200 cm. Rainfall precipitation is rare in the region. Snow precipitation from snow storms is reported to be less than 20 cm (7.9 in.) of snow in nearly 50% of the storms, even though one observatory in the region has reported 80 cm (31.5 in.) of snowfall. The precipitation starts melting from May. Snow on slopes is generally slackly bonded, with wind redistributing it. The average total snowfall recorded in a year is reported to be 12 m (39.4 ft)–15 m (49.2 ft) with temperatures of Highest Max. 13°C (55.4°F), Mean Max. 0.5°C (32.9°F), Mean Minimum minus 11.7°C (53.1°F), and Lowest Minimum of minus 27°C (80.6°F). The ground in the zone is covered with scree and boulders.
Altitude	High-altitude lake, 4,883 m above mean sea level
Surface area	The lake is fed from the glaciers and torrential nullahs (streams) originating from the Bara-lacha-la pass, which is 8 km (5.0 miles) long and is also called the “Pass with crossroads on summit” since roads from Zaskar, Ladakh, Spiti, and Lahaul meet at this pass. In addition to the Suraj Tal and the Bhaga River that originates from it, Bara-lacha-la Pass is also the source of the Chandra and Yunan Rivers in the northwest and north, respectively.
Inflow	Glacier and snow melt
Outflow	Bhaga river
Ecological status	Frozen during winter
Recreation	Lahaul Spiti valley is a common destination for Indian and foreign tourists for road trips, trekking, and motorcycling which cover the lake and the Bara-lacha-la pass, en-route from Manali to Leh. Motorcycle trips during the season when the area is approachable are undertaken by tourists. During such trips from Manali to Leh, the section between Patseo to Bara-lacha-la is a rough journey of 30 km (18.6 miles). Along this route, two small lakes, the Deepak Tal and the Suraj Tal are seen.

Indian Lakes, Table 1 (Continued)

Studies undertaken	Trekking tours are a common feature. One such trek route is the Zingzingbar–Suraj Tal–Bara-lacha-la, which involves trek along the Bhaga River for 3 km (1.9 miles), cross a bridge to the North bank, then a further climb of 2.5 km (1.6 miles) from the bridge followed by a steep foot trail up to Suraj Tal. The lake's geology is represented by the Bara-lacha-la Pass, which is reported to be an early rifting event on the northern Indian passive margin and that the Basalts which are emplaced along the trans-tensional faults indicate that. The Bhaga Valley (Tod or Stod Valley) formed from Suraj Tal up to Tandi, the confluence point with Chandra River, is 64 km (39.8 miles) long (Hoybye, 1997). The valley, which is a narrow gorge, is devoid of any vegetation up to Darcha and thereafter it widens up to its confluence with Chandra River at Tandi with terraces between Darcha and Tandi which are under cultivation in the lower slopes, with the middle slopes having grasslands. Plantation of trees and shrubs to meet fuel wood and fodder requirements has been done on the hill slopes.
General	Patseo and Darcha are the mountain hamlets near the lake.
Lake	Chandra Tal, Himachal Pradesh
Location	Situated in the Spiti district of Himachal Pradesh (India), 6 kms away from the Kunzum Pass in Spiti and Lahaul district of Himachal Pradesh, India.
Location on map	32°28'31"N 77°37'01"E32.47518°N
Climate	The days are not cold but the temperature drops quickly after the sun sets, and the wind adds its bit. The best way to keep warm is to wear clothes in layers
Altitude	4,300 m above mean sea level in the Himalayas
Surface area	Boasting of a circumference of about 2.5 km, the deep blue water of Chandra Tal lake is the source of the Chandra river.
Inflow	The lake is situated on a plateau (Samudra Tapu) overlooking the Chandra River which originates from a glacier near Bara-lacha-la.
Outflow	A clear stream of water flows out of the lake. During the day, the lake appears prussian blue in color, and a greenish tinge appears toward the evening.
Ecological status	The Chandra Tal trek is rated moderate by most people. You can feast your eyes with the unparalleled beauty of this landscape, unique in many respect compared to the other Himalayan treks. The clear blue sky and the rugged brown rolling mountains, almost treeless, form a picture perfect image. This landscape goes on for miles interspersed with lush green meadows, and the sparkling Chandra river down below.
Biodiversity	The mountain peaks with snow caps and slopes around the valley rise up to 3,000–6,300 m. The mountain ranges are called Moukila and Chandrabhaga which challenge mountaineers. This crystal clear blue water lake lies in a broad grassy plain, which in ancient times was a glacier. Ideal for camping, can be approached from Manali and by Kaza.
Recreation	Mountains of scree overlook the lake on one side, and a magnificent cirque presents a view on the other. The name of the lake originates from its crescent shape. Chandra Tal is a popular destination for trekkers and campers. The lake is accessible on foot only for few months in a year, from May to August. Vast meadows are the camping sites on the banks of the enchanting lake. During spring season, it is carpeted with hundreds of kinds of wild flowers.
Commercial use	The Chandra Tal lake, once a halting place for traders who went to Spiti and Kullu valley from Tibet and Ladakh, attract a large number of adventure lovers.
General	From June to September a large number of tourists visit the lake. This is also the time when shepherds from Kangra, Mandi, and Kullu can be seen with their herds of sheep at Chandra pastures. According to legend, this lake is the location from where God Indra's chariot picked up Yudhishtira, the eldest of the Pandava brothers. As a result, this lake is a revered one and draws a large number of devotees.
Lake	Pangon Tso lake in Sikkim, India
Location	100 km southeast of Leh Ladakh, Jammu and Kashmir, India; Rutog County, Tibet
Location on map	33°43'04.59"N 78°53'48.48"E
Climate	Cold arid climate
Altitude	4,218 m above mean sea level
Surface area	The lake area is about 65,000 ha. Maximum depth of water in the lake is about 100 m. Max. length 134 km (83 miles) Max. width 5 km (3.1 miles) Surface area approx. 700 km² (270 miles²) Surface elevation 4,250 m (13,940 ft)

Indian Lakes, Table 1 (Continued)

Inflow	Input to the lake is precipitation during summer as well as winter season. Due to snowfall, thawing of catchment vegetation takes place due to which there is heavy catchment erosion during summer rainfall. Since the lake is in the valley, all the sediment load comes into the lake along with the runoff. Formerly, Pangong Tso had an outlet to Shyok River, a tributary of Indus River, but it was closed off due to natural damming. Two streams feed the lake from the Indian side, forming marshes and wetlands at the edges. Strand lines above current lake level reveal a 5 m (16 ft) thick layer of mud and laminated sand, suggesting the lake has shrunk recently in geological scale.
Type of lakes	Natural high-altitude narrow brackish lake
Ecological status	• Lake gets frozen in winter. • Overturning in the lake takes place in December and January. • Lake has a protected high-altitude cold desert National Park.
Changes over the last years	Due to decreasing trend of rainfall and accelerated sedimentation, the lake is shrinking, though quantitative data on lake shrinkage are not available.
Biodiversity	The brackish water of the lake is devoid of any micro-vegetation. Guides report that there are no fish or other aquatic life in the lake, except for some small crustaceans. On the other hand, visitors see numerous ducks and gulls over and on the lake surface. There are some species of scrub and perennial herbs that grow in the marshes around the lake. The lake acts as an important breeding ground for a variety of birds including a number of migratory birds. During summer, the Bar-headed goose and Brahmini ducks are commonly seen here. The region around the lake supports a number of species of wildlife including the kiang and the marmot.
Recreation	Center of international tourism.
Commercial use	The lake is a strategic site situated in upper drainage basin of Indus river. In the first week of June every year, an annual fair takes place around this lake. This annual fair is called "Sindhu Darshan."
Studies undertaken	Limnological and biological study
Governing authority	Sikkim State Government
General	Pangong Tso is in disputed territory. The Line of Actual Control passes through the lake. A section of the lake approximately 20 km east from the Line of Actual Control is controlled by China but claimed by India. The eastern end of the lake is in Tibet and is not claimed by India. The western end of the lake is not in dispute. After the mid-nineteenth century, Pangong Tso was at the southern end of the so-called Johnson Line, an early attempt at demarcation between India and China in the Aksai Chin region. The Khurnak Fort (33°46'00"N 79°00'00"E/33.766667°N 79.000000°E/33.766667; 79.000000) lies on the northern bank of the lake, halfway of Pangong Tso. The Chinese controlled Khurnak Fort area by the end of 1952, as is the situation today. On October 20, 1962, Pangong Tso saw military action during the Sino-Indian War, successful for People's Liberation Army. Pangong Tso is still a delicate border point along the Line of Actual Control. Incursions from Chinese side are common.
Lake	Roopkund lake, Uttarakhand
Location	In Chamuli district of Uttarakhand
Location on map	30°15'43"N 79°43'55"E/30.262°N
Climate	The climate is hostile during most of the year. One gets a closer view of Trisul and other peaks higher than 5,000 m. Many waterfalls and landslides are visible on the extreme slopes of the surrounding mountains.
Altitude	About 5,029 m above mean sea level.
Type of lakes	A glacial lake in Uttarakhand state of India famous due to more than 500 skeletons found at the edge of a lake. The location is uninhabited and is located in Himalaya.
Recreation	Roopkund is a picturesque and beautiful tourist destination in the Himalayas, located near the base of two Himalayan peaks: Trisul (7,120 m) and Nandghunthi (6,310 m). A religious festival is held at the alpine meadow of Bedni Bugyal every autumn with the nearby villages participating. A larger celebration, the Nanda Devi Raj Jat, takes place once every 12 years at Roopkund. Skeleton lake is covered with ice for most of the time during the year. However, the journey to Roopkund is an enjoyable experience. All along the way, one is surrounded by mountain ranges from all sides.

Indian Lakes, Table 1 (Continued)

Studies undertaken	There are different routes for a trek to Roopkund. Generally, trekkers and adventurers travel to Lohajung or Wan by road. From there, they climb a hillock at Wan and reach Ran ki Dhar. There is some flat area where trekkers can camp for the night. If the sky is clear, one can see Bedni Bugyal and Trisul. The next camping spot is at Bedni Bugyal, which is 12–13 km from Wan. There is a huge grazing ground for mules, horses, and sheep. There are two temples and a small lake that add to the beauty of this place. One can see many Himalayan peaks from Bedni Bugyal bridge. Trekkers then go up to Bhaguwabasa, which is 10–11 km from Bedni Bugyal. From Bhaguwabasa, trekkers either go to Roopkund and come back, or they go to Shila Samundra (Ocean of Stones) via Junargalli Col Pass, which is just above the lake, and then proceed with the trek up to Homkund. The human skeletons were rediscovered in 1942 by a Nanda Devi game reserve ranger H. K. Madhwal, although there are reports about these bones from late nineteenth century. Earlier it was believed by specialists that the people died from an epidemic, landslide, or blizzard. The carbon dating from samples collected in the 1960s vaguely indicated that the people were from the twelfth century to the fifteenth century. In 2004, a team of Indian and European scientists visited the location to gain more information on the skeletons. The team uncovered vital clues including jewelry, skulls, bones, and preserved tissue of bodies. DNA tests on the bodies revealed that there were several groups of people including a group of short people (probably local porters) and a taller group who were closely related – with DNA mutations characteristic for Kokanastha Bramins in Maharashtra. Though the numbers were not ascertained, remnants belonging to more than 500 people have been found and it is believed that even more than 600 people perished. Radiocarbon dating of the bones at Oxford University Radiocarbon Accelerator Unit determined the time period to be AD 850 $\pm$ 30 years. After studying fractures in the skulls, the scientists in Hyderabad, Pune, and London determined that the people died not of disease, but of a sudden hailstorm. The hailstones were as large as cricket balls, and with no shelter in the open Himalayas, all of them perished. Furthermore, with the rarefied air and icy conditions, many bodies were well preserved. With landslides in the area, some of the bodies made their way into the lake. What is not determined was where the group was headed to. There is no historical evidence of any trade routes to Tibet in the area but Roopkund is located on an important pilgrimage route of Nanda Devi cult with Nanda Devi Raj Jat festivities taking place approximately once in 12 years.
Lake Location Location on map Climate Altitude Surface area Inflow Type of lakes Changes over the last years	Harike lake in Punjab Harike or Hari-ke-Pattan, as it is popularly called, is the nearest town to the wetland. Makhu (Ferozepur) is the nearest railway station, and the bus stand is situated 10 km south of the Harike town, which connects to Ferozepur, Faridkot, and Bhatinda by the National Highway. The headworks built on the Sutlej River downstream of its confluence with Beas River and the reservoir created, which form the Harike lake and the enlarged wetland, is a purposeful project, which acts as the Headworks for irrigation and drinking water supplies, through the Ferozepur, Rajasthan, and Makku feeder canals with total carrying capacity of 29,000 ft³/s (820 m³/s), to supply to the command areas located in the states of Punjab and Rajasthan. The grand Indira Gandhi Canal in Rajasthan is fed from this source. The lake is triangular in shape, with its apex in the west, bounded by a bund called the Dhussi Bund forming one side, a canal in the second, and a major road on the third. The periphery of the lake is surrounded by agricultural land and the wetland is reported to be rich in groundwater resources. 31°10'N 75°12'E 31.17°N Monsoon climate dominates the catchment draining into the wetland. 210 m above mean sea level 4,100 ha. Average depth is few centimeters whereas maximum depth is around 200 cm. Beas and Sutlej Rivers Freshwater The wetland which is in existence since 1953 underwent changes over the years due to several factors, some of which are the following: • Encroachments on the wetland habitat for intensive agriculture with resultant effluents of agricultural chemicals and also controversial encroachments. • Utilization of surface and groundwaters for irrigation • Effluent discharge of untreated waste from towns and villages from industrial, urban, and agricultural activities into the rivers which feed the wetland resulting in extensive weed growth (Water Hyacinth) in the wetland (polluted water discharged was reported to be about 700 million liters per day (mld)) • The profuse growth of water hyacinth had covered 80% of the open water surface resulting in the 33 islands getting enclosed.

Indian Lakes, Table 1 (Continued)

Biodiversity

- Soil erosion and siltation due to deforestation of the fragile lower Shivalik hills which form the catchment of the wetland.
- Illegal fishing and poaching in spite of the Wildlife (Protection) Act.
- Indiscriminate grazing in the catchments resulting in damage to the wetland ecology.
- A remote sensing study of the Wetland area coupled with the analysis of rainfall, discharge, and groundwater level showed that the flow pattern had diminished and the size of wetland area had reduced by about 30%, over a 13 years study period ([Indian Meteorological Department's Atlas for maximum possible sunshine duration](#)).
- The ecological crisis had reached such a stage that environmentalists estimated lifespan of the wetland to be decreasing.

Harike Wetland also known as "Hari-ke-Pattan," with the Harike lake in the deeper part of it, is the largest wetland in northern India in the Ferozepur district of the Punjab state in India. The wetland and the lake were formed by constructing the head works across the Sutlej river, in 1953. The headworks is located downstream of the confluence of the Beas and Sutlej rivers. The rich biodiversity of the wetland which plays a vital role in maintaining the precious hydrological balance in the catchment with its vast concentration of migratory fauna of waterfowls including a number of globally threatened species (stated to be next only to the Keoladeo National Park near Bharatpur) has been responsible for the recognition accorded to this wetland in 1990, by the Ramsar Convention, as one of the Ramasar sites in India, for conservation, development, and preservation of the ecosystem.

The rich biodiversity of the wetland, with several species of birds, species of turtles, species of snakes, taxa of amphibians, taxa of fishes, and taxa of invertebrates, is reportedly unique.

The wetland was declared a bird sanctuary in 1982 and named as Harike Pattan Bird Sanctuary with an extended area of 8,600 ha (Geological Survey of India & Report, 1988). Bombay Natural History Society (BNHS) carried out research and a bird ringing program during the period 1980–1985 (Cavazza, 1993). An Ornithological field laboratory was proposed to be established by BNHS.

Two hundred species of birds visit the wetland during winter season of which some of the well-known species are the (1) Cotton Pygmy Goose (genus *Nettapus*), (2) Tufted Duck (*Aythya fuligula*), (3) Yellow-crowned Woodpecker (*Dendrocopos maharattensis*), (4) Yellow-eyed Pigeon or Pale-backed Pigeon, (5) Water Cock (*Gallicrex cinerea*), (6) Pallas's Gull or Great Black-headed Gull (*Ichthyiaetus ichthyiaetus*), (7) Brown-headed Gull (*Chroicocephalus brunnicephalus*), (8) Black-headed Gull (*Chroicocephalus ridibundus*), (9) Yellow-footed Gull (*Larus michahellis*), (10) Indian Skimmer (*Rynchops albicollis*), (11) White-winged Tern (*Chlidonias leucopterus*), (12) White-romped Vulture, (13) Hen Harrier (*Circus cyaneus*), (14) Eurasian Tree Sparrow (*Passer montanus*), (15) Hawk (subfamily Accipitrinae), (16) Eurasian Hobby (*Falco subbuteo*), (17) Horned Grebe (*Podiceps auritus*), (18) Black-necked Grebe (*Podiceps nigricollis*), (19) Great Crested Grebe (*Podiceps cristatus*), (20) White-browed Fantail (*Rhipidura aureola*), (21) Brown Shrike (*Lanius cristatus*), (22) Common Woodshrike (*Tephrodornis pondicerianus*), (23) White-tailed Stonechat (*Saxicola leucurus*), (24) White-crowned Penduline-tit (*Remiz coronatus*), (25) Rufous-vented Prinia (*Prinia burnesii*), (26) Striated Grassbird (*Megalurus palustris*), (27) Cetti's Warbler (*Cettia cetti*), (28) Sulphur-bellied Warbler (*Phylloscopus griseolus*) and (29) Diving duck (pochards).

The wetland's rich floating vegetation comprises the following:

- *Eichhornia crassipes* dominates in 50% area.
- *Azolla* sp. is sparsely seen in open water areas.
- *Nelumbo nucifera*, the Lotus, the prominent rooted floating vegetation.
- *Ipomoea aquatica*, at the lake periphery in the shallower region.
- *Najas*, *Hydrilla*, *Ceratophyllum*, *Potamogeton*, *Vallisneria* (eelgrass, tape grass vallis) and Charales are the species of submerged vegetation.
- *Typha* sp. is the dominant emergent marsh vegetation.
- Tiny floating islets are formed by *Eichhornia crassipes* and other grass species in the mud and root zone all over the wetland.

Dalbergia sissoo, *Acacia nilotica*, *Zizyphus* sp, *Ficus* sp, alien *Prosopis juliflora* in large clumps and other trees are planted along the embankment. The State Wildlife Department has constructed earthen mounds in the marsh area with trees planted on it to increase nesting sites for the birds.

Studies undertaken

This man-made, riverine, lacustrine wetland spreads into the three districts of Amritsar, Ferozepur, and Kapurthala in Punjab and covers an area of 4,100 ha. Conservation of this wetland has been given due importance, since 1987–1988, both by the Ministry of Environment and Forests, Government of India and the Punjab State Government (through its several agencies), and over the years several studies and management programs have been implemented.

The Punjab State Council for Science & Technology has reported that the water quality of the lake is mostly of "A" Class as per the designated best use criteria even though large volumes of polluted water discharge into the wetland from industries and urban centers.

Indian Lakes, Table 1 (Continued)

Governing authority	The gravity of the degraded status of the wetland has been addressed for implementing several restoration measures by a plethora of organizations/agencies/research institutions of the central and state governments and also the Indian Army Units located in the area. The measures undertaken to conserve the wetland have covered the following actions. The Chief Minister of the State of Punjab instituted, in 1998, the Harike Wetland Conservation Mission to: - Prepare a Master Plan for the integrated conservation and development of the Harike wetland - Undertake specific projects and programs for the conservation of the ecosystem of the Harike region - Regulate, screen, and monitor all development activities which have a bearing on the Harike wetland ecosystem - Evaluate all plans and proposals of all departments of the Government which concern the future of Harike The menace of water hyacinth was addressed by the Indian Army (Western Command, Vajra Corps.) in the year 2000, in a joint effort initiated by the Chief Minister of the State. Under the Pilot Project named "Sahyog" the Army adopted several innovative mechanical system of weed removal. The Army General reporting on the progress of the works stated: Through a number of innovative methods, we succeeded in making dynamic booms, winches, etc. After the operation, we have placed static and dynamic booms at strategic points in the Harike lake to hold back the floating mats of water hyacinth so that it does not spread. At the end of 6 months of untiring labor by our team, we had opened four channels, which had got choked with silt over the years. We also planted 750 saplings of plants of 2 years of age on the island for birds to nest and roost in future. - The Punjab State Council for Science and Technology evolved a management plan which involved (Dooge, 1975): - Opening of sluice gates during monsoon - Monitoring of water quality migration period - Fencing some of the selected portions from encroachment - Afforestation of the catchment area - Survey, mapping, and notification - Soil conservation - Education and Public awareness
Lake	Kanjli Wetland, Punjab
Location	Kanjli wetland which subsumes the Kanjli lake is located in the Kapurthala district of Punjab state in India and was created in 1870 by constructing the headworks across the perennial Bien River, a tributary of the Beas River to provide irrigation facilities to the hinterland. The Kanjli ecological Wetland region around the village Kanjli is 4 km (2.5 miles) from the Kapurthala town, also the district headquarters, and is thus well connected by road network to all parts of the state and rest of the country.
Inflow	The Kali Bein River, originating near village Dhanoa, upstream of Budho Bark Regulator in Hoshiarpur District, formerly a main tributary of the Beas River feeds the Wetland and the lake. The Bein has now become an independent river due to siltation and westward swing of the Beas River. Agricultural development dominates the catchment of the wetland. The Bein River has contributed to the formation of fertile plains by bringing down large sediment loads during floods. Depth of water in the lake has a seasonal variation of 3.05 m (10 ft) to 7.62 m (25 ft) depending on the season and inflow discharge. Catchment area is mainly under agriculture. The wetland is in the semi-arid zone and receives an average annual rainfall of about 620 mm. The temperature varies from a maximum of 45°C in summer to an average of 60°C during winter with occasionally freezing temperatures. The Kali Bein and its wetland provide water supply for agriculture in the Kapurthala district, recharges the groundwater, drains excessive rainwater from sensitive crops like wheat, potato, etc., and acts as a sponge by absorbing the floodwaters.

Indian Lakes, Table 1 (Continued)

Type of lakes	A man-made wetland
Ecological status	The Kanjli Wetland is one of the man-made wetlands in India identified by the Government of India, as per the Expert Group's (set up in 1983 by the Ministry of Environment and Forests) report published in 1990. The Expert Group has based its directory on the basis of the definition enunciated by the Ramsar International Convention on Wetlands: “Areas of marsh, fen, peatland, or water whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters.” Further, considering the definition of wetlands given by Cowden in 1979 for classification of wetlands in USA, three key attributes of hydrology (the degree of flooding or soil saturation), wetland vegetation (hydrophytes), and hydric soils have also been considered for identification. In this list, Mangroves are not included since it falls under a separate category. The Expert Group's directory has made a distinction between Natural and Man-Made wetlands (including wetlands of less than 100 ha area). In India, in its 24 states and two union territories (as per the 1990 report), there are 2167 number of natural wetlands with a total area of 1.45 million hectares and Man-Made wetlands of 65,254 number with total area of 2.59 million hectares. The inland water bodies listed in the report cover lakes, tanks, reservoirs, etc.
Changes over the last years	In the Wetland, the ecological status of the Kanjli lake, in particular, has been threatened on account of the following issues: • Extensive growth of water hyacinth due nutrients and pesticides from adjoining agricultural fields • Anthropogenic pressure and consequent land encroachment • Eutrophication, particularly due to in situ decay of hyacinth • Conversion of wetland for agriculture, human habitation, industrial expansion, and recreational activities • Illegal and indiscriminate fishing causing disturbance to bird life
Biodiversity	The rich biodiversity of the wetland comprising aquatic, mesophytic, and terrestrial flora and fauna, including some important species of plants and animals, was recognized internationally by the Ramsar Convention in 2002 by designating the Kanjli lake in the List of Wetlands of International Importance. In this context, it is reported that in Punjab State, which has 14 wetlands covering an area of 225.76 km² (Two per cent of the geographical area of the State), three of its wetlands, namely the Kanjli Wetland (covering an area of 490 ha of which the Kanjli lake water spread is 184 ha), the Harike Wetland (4,100 ha), and the Ropar Wetland (1,365 ha) have been chosen by the Ministry of Environment and Forest (MoE&F), Government of India, for their conservation and management and are now also included in the Ramsar list covering a total area of 5,650 ha. Kanjli is upstream of Harike Wetland located in the Beas river basin, while the Ropar Wetland is in the Roopnagar district. The flora and fauna recorded in the Wetland and the Kanjli lake within it (some of them are pictured in the gallery) are the following: • Twelve varieties of trees recorded in the wetland are (1) <i>Acacia arabica</i>, (2) <i>Albizia lebbek</i>, (3) <i>Azadirachta indica</i>, (4) <i>Dalbergia sissoo</i>, (5) <i>Eucalyptus hybrid</i>, (6) <i>Ficus bengalensis</i>, (7) <i>Mangifera indica</i>, (8) <i>Melia azedarach</i>, (9) <i>Morus alba</i>, (10) <i>Prosopis juliflora</i>, (11) <i>Syzygium cumini</i> and (12) <i>Ziziphus mauritiana</i> • Shrubs recorded are <i>Calotropis procera</i>, <i>Ipomoea crassicaulis</i>, and <i>Tamarix dioca</i> • Herbs noted are <i>Saccharum munja</i>, <i>S. spontaneum</i>, <i>Scirpus</i> sp., and other common herbs. 11 species of aquaflora, 34 species of zooplankton, and 15 species of macroinvertebrate species have been reported. <i>Aqua fauna</i> According to the District Gazetteer and the study done by the National Environmental Engineering Research Institute (NEERI), 17 fish species (in Bein river and the lake) have been reported which includes the common fish species of <i>Catla catla</i>, <i>Channa marulius</i> (Great snakehead), <i>Cyathus striatus</i>, <i>Cirrhinus mrigala</i>, <i>Labeo calbasu</i>, and <i>L. rohita</i>. The tortoise is the common reptile reported in the area. Birds found in the wetland are of two varieties, viz., common resident birds (28 species) and the migratory birds of nine species. The migratory birds are: (1) Various species of goose, (2) White eyed pochard, (3) Wigeon, (4) Tufted pochard, (5) Common Teal, (6) Large whistling teal, (7) Pintail, (8) Mallard and (9) Shoveller <i>Fauna</i> The mammalian fauna seen in the wetland are (1) the Indian civet, (2) mongoose, (3) Indian porcupine, (4) squirrel, and (5) common Indian hare.

Indian Lakes, Table 1 (Continued)

Studies undertaken	The water and sludge quality of the wetland has been studied by the Punjab Pollution Control Board. Their report indicates that quality generally conforms to Class “B” with some degree of quality degradation to Class “D” sometimes during December. From a satellite imagery study of the wetland it has been inferred that Kanjli lake could be categorized under low turbidity class (dark blue hue) during pre-monsoon period and moderate turbidity class (medium blue) during post-monsoon season which is indicative of regimentation occurring in the lake during post-monsoon season.
Governing authority	The erstwhile Maharaja of Kapurthala (Raja Randhir Singh – 1862–1870) built the headworks on the river Kali Bein that resulted in the creation of the Kanjli Wetland which subsumes the sparkling lake by the same name. The Maharaja also built a retreat, in the French architectural style, in the forest set in lovely natural scenery, on the banks of the lake, which was named “The Villa” or the “Villa Buona Vista.” His royal successors live in this retreat even now. The lake has been developed as a tourist destination with facilities for fishing and boating. A traditional Mela or exhibition is held here during Deepavali festival.
General	Conservation measures The conservation and management measures undertaken with assistance provided by the Ministry of Environment & Forests, Government of India (MoEF, GOI) by the Environment Division of the Punjab State Council for Science & Technology under the Directive of the State Level Steering Committee are the following (Indian Meteorological Department's Atlas for maximum possible sunshine duration): • Detailed mapping of the wetland for declaring and notifying the Kanjli Wetland as protected area under the Environment Protection Act, 1986. • Judicious Hyacinth (weed) control by the Irrigation department, District Police, and even the Army Units, by manual methods. Conveyor belt system as a Mechanical method to clear the weeds is also being tried. • Hyacinth control through biological control by releasing two weevil species (which have proved been found effective world wide and introduced in the downstream in the Harike Wetland Ecosystem) of <i>Neochetina bruchi</i> and <i>N. eichorniae</i>. Release of moth <i>Sameodes albiguittal</i> is also being considered as an option. • Introduction of more fish species in the lake judiciously to avoid any adverse effects of exotic species. • Afforestation measures around the lake area and in the small islands, with mixed indigenous species of trees to prevent soil erosion resulting in siltation reduction in the lake, to attract large species of birds to nest and roost and to enhance the ecosystem. • Selective fencing of the wetland to prevent excessive grazing to preservation of important pockets provide habitat for wading birds and to check encroachments. • Monitoring of water quality continuously to check the degree of external nutrient loading of the lake waters and to evolve appropriate preventive and curative steps. • Public awareness campaigns through mass media, educational material, camps, etc., of the wetland ecosystem with the help of Voluntary Organizations. • Continued scientific research on Biological and hydrological components, and Productivity potential with respect to economic value, social aspects of heritage and to rate the significance of the wetland.
Lake	Ropar Wetland, Punjab
Location	Ropar Wetland, also named Ropar lake is located close to the Rupnagar city, 45 km northwest of Chandigarh City, in Roopnagar and Nawanshahr districts of Punjab. Chandigarh is the nearest airport, which connects to the rest of India.
Location on map	31°01'N 76°30'E 31.02°N 76.50°E
Climate	Climatically, the drainage area of the wetland falls under semi-arid zone of Punjab with mean annual rainfall of 1,518 mm. Initially, in the year 1882, a small headwork was constructed on the right bank of Sutlej River, near Ropar town, to supply water to Sirhind Canal. Subsequently, in 1952, a head regulator was constructed to divert water not only to the Bist Doab Canal but also to Sirhind Canal and to the Bhakra Main Canal (upstream of the wetland), for irrigation, industrial, and domestic use.
Altitude	275 m above mean sea level.
Surface area	The total area covered by the wetland is 1,365 ha, which includes 800 ha area of the river and the reservoir, 30 ha of forest area named as “Sadavarat Forest,” and 30 ha under marshy plants. Average depth is 0.5 m, where as maximum depth is 6 m. The wetland is surrounded by hills in the northwest and by plain area in the south and southeast.

Indian Lakes, Table 1 (Continued)

Inflow	Sutlej River
Type of lakes	A man-made freshwater riverine and lacustrine wetland.
Ecological status	This important ecological zone is located in the Shivalik foothills of the Lower Himalayas and was created in 1952 on the Sutlej River, in the Punjab state of India, by building a head regulator to store and divert water for beneficial uses of irrigation, drinking, and industrial water supply. <i>Flora and fauna</i> The wetland is rich in flora and fauna which are categorized below. <i>Flora</i> A total of 19 species of trees and 14 species of bushes and grasses are recorded. Of these, the tree species are (1) <i>Acacia catechu</i>, (2) <i>Ameles modesta</i>, (3) <i>Acacia nilotica</i>, (4) <i>Albizia lebbek</i>, (5) <i>Azadirachta indica</i>, (6) <i>Bombax ceiba</i>, (7) <i>Cassia fistula</i>, (8) <i>Dalbergia sissoo</i>, (9) <i>Eucalyptus tereticornis</i>, (10) <i>Ficus benghalensis</i>, (11) <i>Ficus religiosa</i>, (12) <i>Mangifera indica</i>, (13) <i>Melia azedarach</i>, (14) <i>Moringa oleifera</i>, (15) <i>Morus indica</i>, (16) <i>Prosopis juliflora</i>, (17) <i>Salix willow</i>, (18) <i>Syzygium cumini</i> (Jambul), and (19) <i>Zizyphus jujuba</i>. <i>Aqua fauna</i> Wetland is a major source of fisheries since large species of fishes have been recorded; some of the commercially important ones are: • Rohu; <i>Labeo gonius</i> Seerha; <i>Labeo calbasu</i> Kalbans or Dhari; <i>Labeo dero</i> Gid; <i>Labeo dyocheilus</i> (Kunni); <i>Catla catla</i> Thal; <i>Cirrhinus mrigala</i> Mori; <i>Puntius sarana</i> Puthi; <i>Cyprinus carpio communis</i> (Common Carp); <i>Cyprinus carpio spicularis</i> (Mirror carp); <i>Ceenopharyngodon idelle</i> (Grass Carp); <i>Wallago attu</i> Mali; <i>Aorichthys seenghala</i> Sangarha; <i>Mastacembelus armatus</i> Sam (Tire track eel); <i>Ambassis ranga</i> Shisha Mach; <i>Channa punctatus</i> Dolla (Snake-headed fish); and <i>Channa striata</i> Curd. • Four species of Amphibia (Frogs) have been noted. <i>Avi fauna</i> Several species of birds have been recorded which include 49 species of local birds, 11 species of migratory birds, 3 species of rare birds, and 54 species of common birds. Some of the rare birds among the migratory birds noted are: <i>Dinopium benghalense</i>; Golden-backed Woodpecker; <i>Megalaima haemacephala</i>; Crimson-breasted barbet; and <i>M. zeylanica</i> Green barbet <i>Fauna</i> Two species of tortoise, viz., <i>Geoclemys hamiltonii</i> and <i>Chitra indica</i> (endangered species), five species of lizards, 11 species of snakes including the threatened species of <i>Python molurus</i> or Indian python or ajar are found in the wetland. <i>Food chain</i> The food chain in the wetland is basically well balanced as it has both deepwater and shallow water characteristics, and the ecosystem is stated to be almost self-sufficient and self-regulating.
Changes over the last years	Over the years several adverse impacts on the quality of the wetland have been reported. Some of the important ones which invited remedial actions are: • Acute problems of siltation from the adjoining barren and fragile hills. Bare hills of the catchment are subject to continuous erosion leading to shrinkage of wetland area. • Unwarranted interference with the resident and migratory birds. • Unauthorized fishing and poaching of wildlife causing damage to species. • Increase in effluents from industrialization in the upstream area of the wetland, such as the Fertilizer plant at Nangal and Thermal Power Plant at Ropar. • Effluents of chemical pollutants like agrochemical residues runoff, industrial effluents, and sewage from some towns in the upper reaches of the wetland. • Growth of invasive weeds.
Biodiversity	The area has at least 9 mammal, 154 bird (migratory and local), 35 fish, 9 arthropod, 11 rotifer, 9 crustacean, and 10 protozoan species, making it biologically diverse. The endangered turtle <i>Chitra indica</i> and the threatened snake <i>Python molurus</i> (at lower risk) are reported to be residents in the wetland. Considering the wetland's diverse and rich biodiversity, Ramsar Convention has included Ropar Wetland (listed as Ropar lake) as one of the Ramsar sites among the 21 sites listed under India, for "the conservation of global biological diversity and for sustaining human life through the ecological and hydrological functions they perform."
Recreation	The wetland is a popular tourist attraction for bird watching and boating. A tourism complex called the "Pincasia" is located within the wetland boundary, which is run by the Punjab Tourism Development Corporation. A Boat Club is also functioning.
Commercial use	Agricultural crops such as wheat, rice, sugarcane, sorghum, etc., are grown in the farmlands in the area surrounding the wetland but the hills have thin vegetation and are exposed to intensive grazing.

Indian Lakes, Table 1 (Continued)

Studies undertaken	Water Quality that determines the health of ecosystem of the wetland was monitored by the Punjab Pollution Control Board (PPCB) in the year 1998–1999. The water quality was reported to be of “A” category as the river entered into Punjab and deteriorated to “D” category downstream of Ropar lake, mainly due to the industrial effluents from a number of factories and industrial units. Further studies on physico-chemical analysis of important parameters, biological estimations as well as pesticide residue analysis have been initiated. A scientific study of the food chain has brought out the following sequence of facts: • Sunlight, pH, inorganic salts, nutrients, and dissolved gases are the main abiotic components of the wetland ecosystems with the organic matter caused by the death and decay of animals and plants accumulating at the bottom of the lake. • Decomposition at the bottom of the lake takes place due to a variety of heterotrophic microbes such as bacteria, actinomycetes, and fungi; <i>Aspergillus</i> sp., <i>Rhizopus</i> sp., <i>Curvularia</i> sp., <i>Paecilomyces</i> sp., <i>Saprolegnia</i> sp., etc., are main species causing the decomposition. • The producers of organic matter are the eutrophic green plants and some photosynthetic bacteria; the rooted submerged, floating, and emergent hydrophytes being the <i>Typha</i> sp., <i>Eleocharis</i> sp., <i>Sagittaria</i> sp., <i>Nymphaea</i> sp., <i>Potamogeton</i> sp., <i>Vallisneria</i> sp., <i>Eichhornia</i> sp., <i>Lemna</i> sp., etc., and minute, floating, or suspended lower plants like filamentous algae, diatoms, chlorococcales and flagellates. • Herbivores such as the mollusks, crustaceans, rotifers, and some insects are the primary consumers which feed directly on plants. • Plant remains and organic matter nourish detritivores like the Chironomidae sp., mollusks, mites, some crustaceans, and small fishes. • Marginal rooted macrophytes are consumed by mammals such as buffaloes, cows, etc., which frequent the shores of the lake. • Hydrophytes are also the food source of some birds. • Carnivores like the Predator beetles and bugs, dragonflies are the secondary consumers which feed on insects, mollusks, rotifers, and crustaceans. Carnivorous fishes also belong to this category. • Large carnivorous fishes and birds are the tertiary consumers which feed on small fishes and insects. • Top most consumer level is that of the human being and the fish eating birds, which feed mainly on fishes.
Governing authority	<i>Restoration measures</i> The Punjab State Council for Science & Technology has evolved several conservation programs with support from the Ministry of Environment and Forests (MoE&F) of the Government of India. Some of the programs implemented include mass awareness campaigns and promotion of public participation in the wetland conservation. A few of the measures planned and under various stages of implementation are: • Afforestation and soil conservation in the highly erosion-prone catchment areas of the wetland. • To erect chain-link fencing of strategic areas of the wetland to prevent exploitation of vital wetland resources and prevent encroachments of the wetland. • Detailed survey, including remote sensing survey and preparation of comprehensive maps. • Detailed taxonomic studies of plant and animal species. • Introduce fish species sustain fragile relationship between the Fish level and the other biotic resources like birds and primary producers and to set up new fish seed farms in addition to refurbish the existing ponds. • Economic assessment.
General	An archaeological museum of the Archaeological Survey of India at Ropar has displays of the antiquities unearthed during the excavations of mound in the area along with photographs displaying excavation material. The Museum depicts a sequence of six cultural periods or phases, with some breaks from Harappan times to the present day, found in the 21 m high ancient mound known as Nalagarh Tibbi overlaying the Shiwalik (also spelt Sivalik) deposition on the left bank of the Satluj River where it emerges into the plains. A deep well with a stone inscription of Emperor Shah Jahan (AD 1627–1658) has been located at the foot of the mound. The excavations have established that advanced civilization similar to the Harappa and Mohenjodaro Civilization prospered in Ropar town, an integral part of the wetland. The wetland area has also a modern history in respect of Anglo–Sikh relations. On 26 October 1831, sitting under the shade of an old ficus tree on the bank of Sutlej River, Maharaja Ranjit Singh and Lord William Bentinck, the British Governor General, signed an agreement defining the Anglo–Sikh relations and territories.
Lake	Sultanpur Jheels in Haryana
Location	Located at 15 km west of Gurgaon.
Location on map	28°28' N and 76° 55' E

Indian Lakes, Table 1 (Continued)

Climate	The climate of the region is monsoon climate with very scanty rainfall.
Altitude	220–230 m above mean sea level
Surface area	Having total area of 13,727 ha.
Inflow	Local inflow during monsoon rainfall.
Outflow	The lakes flood during monsoon and heavy rainfall
Type of lakes	These are a group of shallow freshwater lakes
Changes over the last years	The siltation in the lakes is on the increasing scale. There is an excavation of sand from bed of the lake for lime industry. Planting of the salt-tolerant species in surrounding area and restoration is proposed to reduce erosion.
Biodiversity	It was declared as Bird Sanctuary in 1971.
Studies undertaken	Waterfowl census had been carried out and Avi fauna has been well documented.
Lake	Surajkund, Haryana
Location	Surajkund village, Faridabad district, Haryana. Surajkund is an ancient reservoir of the tenth century, 2 km away to the southwest from a more ancient dam of the eighth century called the Anagpur Dam; both are located in Haryana, India.
Location on map	28°29'01"N 77°18'57"E to 28.48361°N 77.31583°E
Surface area	40 ha
Inflow	The lake's drainage basin is part of the Aravalli hill ranges. It is fed from the northwestern side by a local nallah (stream) that initially feeds the Anagpur dam on the upstream.
Type of lakes	Surajkund (literal meaning is "Lake of the Sun") is an artificial Kund ("Kund" means "lake" or reservoir) built in the backdrop of the Aravalli hills with an amphitheater-shaped embankment constructed in semicircular form.
Changes over the last years	The storage in the tank or lake has been seriously affected since the catchment area contributing flows into the Surajkund (lake) from villages such as Anangpur, Lakkarpur, Ankhir, and Meola Maharajpur has been used for extensive mining and for large habitations, which has disturbed the drainage system and thus obstructed the gravity flow of rainwater from the basin into the reservoir. This situation is stated to have also affected the flora and fauna of the area.
Recreation	In the backdrop of the lake, during the spring season, every year from February 1–15, a colorful traditional craft festival of India is held in the precincts of Surajkund. This fair was first started in 1987. Traditional craftsman (artists, painters, weavers, and sculptors) from all parts of the country participate in this annual celebration named as the "Surajkund Crafts Mela" or "Surajkund designer's Village." Designer items created by 50 best designers and craftsmen in wood, metal, bamboo, iron, glass, textiles, and stone can be seen here. This Mela (fair) is visited by lovers of arts and crafts from all over the world. The fair is held with a different theme every year on Indian culture and crafts. The theme, specific to a state of India, is depicted at the entrance to the Mela grounds and provides an ambience of that particular state with characteristic colors, materials, architecture, furniture, and decorations. The crafts on display in the stalls (400) is of particular crafts of that state. The Mela also includes a food festival covering some of the popular cuisines from different parts of the country. Entertainment in the form of famous rhythms and dance of folk theater are also held here during the festival. During 2009, with Madhya Pradesh as the theme state, 50 crafts persons from SAARC countries, Thailand, and Egypt also participated in the Mela. The show was titled "Hemvati-Khajuraho" as a part of the 23rd annual Surajkund Crafts Fair event. Sanchi Stupa (a world heritage site in Madhya Pradesh) formed the backdrop for the festival. Surajkund, also called the Peacock lake, because of its delightful beauty is now a well-known tourism destination in Haryana state. Activities of water sports such as Kayaking are also an attraction at this lake. It is 8 km (5 miles) by road from South Delhi and 20 km (12 miles) from the heart of the New Delhi city. It is well connected to all parts of the city. The nearest airport is the Indira Gandhi International Airport, 25 km (16 miles) away. The nearest railway stations are the New Delhi Railway Station and the Nizamuddin Railway Station, 22 km (14 miles) and 21 km (13 miles) respectively by road. It is also approached by road and rail from Faridabad (headquarters of the district) and Gurgaon cities. It is 11.5 km (7 miles) from the Qutub Minar and 3 km (2 miles) Tughlaqabad, two historical places in Delhi.

Indian Lakes, Table 1 (Continued)

Studies undertaken	From a study of the prehistoric findings along the ridges of Surajkund reservoir, Anagpur Dam, and around Delhi and adjoining parts of Haryana, it has been inferred that the southern hilly area of Delhi and Haryana was environmentally suited for pre-historic man to settle here. In the Aravalli hill ranges, which spread over Delhi and Haryana, where the Surajkund and the Anagpur Dam are located, ancient Stone Age relics have been revealed. The Aravallis which strike out in two directions from Delhi exhibits a topography of low and rugged hills. The stratigraphy in the area is considered to consist of reddish rocks and scrub and has the luxuriance of the Stone Age progression. Stone Age materials have been unearthed in the region at 43 sites on the road from Delhi to Surajkund and south of the Surajkund-Faridabad road, Anangpur hills and Ankhir pahari on the road on the low ridge from Faridabad to Surajkund. The Stone Age relics comprise Microliths and lower Paleolithics (Indian Meteorological Department's Atlas for maximum possible sunshine duration).
General	It is said to have been built by the Tomar king Suraj Pal of Tomar dynasty in the tenth century. Tomar was a sun worshipper and he had therefore built a Sun temple on its western bank. Another "kund" by the same name as "Suraj Kund" existed in Sunam city, a tahsil and subdivision of the Sangrur District in Punjab. This was devastated by Mahmood Ghaznavi. The temple is now in ruins. According to bardic tradition (a tradition steeped in the history and traditions of clan and country), the Tomar kings who initially lived near the Aravalli hills shifted to the Surajkund area near Lal Kot, which was built by the Tomars. Lal Kot was renamed as Qila Rai Pithora, after Prithvi Raj Chauhan (the second last Hindu king of Delhi). Archaeological excavations have revealed existence of a Sun temple here based on ruins that can be seen even now. Certain carved stones were recently recovered from the reservoir. Some stones have also been reused in subsequent restoration works. Some historians also claim that it was named after King Suraj Pal himself who built it. It is also said that Suraj Pal built this lake for his daughter. During the Tughlaq Dynasty rule of Feroz Shah Tughlaq (1351–1388), the reservoir was refurbished by rebuilding the steps and terraces with stones in lime mortar. On the western bank of the reservoir, a garhi (cave-like structure) was built close to the ancient site of the Sun temple. Though historians have not specifically alluded to this tank, it is also said that it was built in AD 686 by Suraj Pal (after whom the tank is probably named), son of Anang Pal I. It is in the form of a segment (semicircular) with the chord on its west side. Another theory for the name "Suraj" suffixed to the kund (lake) is that it was named after the Sun Temple that existed on the east side of the lake. Even though the Tomar dynasty vanished in the twelfth century, the Surajkund has not been affected. It attracted the attention of the Haryana Government to develop the area as a tourist spot by introducing an annual crafts "Mela" or "fair" titled "Surajkund Crafts Mela" in the precincts of the lake, which over the years has attracted wide publicity and become an iconic event.
Lakes of Western India	
Lake	Pichola lake in Rajasthan
Location	5 km from Udaipur City Railway
Location on map	19°43'N 85°19'E/19.717°N
Climate	Arid climate. Average annual rainfall is 700 mm
Altitude	587 m above mean sea level
Surface area	Presently, area of the lake is about 3.0 km ² , maximum depth of water is about 4.0 m, and minimum depth is about 1.0 m. The lake used to be of 10.5 km ² in area, 8.0 m in maximum depth, and 5.0 m in minimum depth even up to the beginning of twentieth century.
Inflow	Runoff from the catchment area of about 150 km ² of hilly tract.
Outflow	Pichola lake is connected to other lakes in Udaipur City such as Fathesagar lake, Dudh Talai, and Udaisagar lake. Spillway from Pichola goes to Fathesagar, Spillway from Fathesagar goes to Udaisagar through Ayar river, and spillway from Udaisagar goes to river Bechar.
Type of lakes	Pichola lake is a man-made freshwater lake.
Ecological status	Due to rapid deforestation activities in the Aravalies (in catchment area of the lake) sediment load in the lake is increasing year by year. The lake thus created has been filled by sediment deposits to its present level. Non-point source of pollution due to heavy tourist flow to the lake. Pollution mostly includes wastes left by tourists, domestic sewage, etc., into the lake throughout the year.
Changes over the last years	Hydrology of the lake and its catchment has changed over years. The unorganized mining of soil from the lake bed is helping in increasing the capacity of the lake.
Biodiversity	Different types of migratory birds visit the lake during different seasons of the year.

Indian Lakes, Table 1 (Continued)

Recreation	Lake Palace inside the lake and City Palace on the hillock by the side of the lake are famous spots of tourist attraction. These two palaces are the architectural feat of their own time. People from all over the world visit Udaipur City and Pichola lake to see the majestic lake and enjoy boating as well as fishing in the lake.
Commercial use	The lake houses Hotel lake Palace. The commercial value of lake is related to the commercial value of the Hotel. The economy of city of Udaipur is totally dependent on the amount of water in the lake, as tourists get drawn to the lake when the lake is full.
Studies undertaken	Limnological studies by Sukhadia Univeristy at Udaipur. National Institute of Hydrology, Roorkee, India has taken studies for detailed hydrological investigations of Pichola lake and development of model for hydrological processes for the lake and its catchment.
Governing authority	Rajasthan State Government Maharana of Mewar Memorial Foundation
General	Pichola lake was constructed during the period of 1382–1411. Present status of Pichola Lake is such that the lake has completely dried up. Lake Palace Authority just maintains a channel for ferrying to Lake Palace.
Lake	Jaismond lake in Rajasthan
Location	Situated in the valley of Aravalies, 51 km from Udaipur.
Location on map	
Climate	Semiarid climate, annual average rainfall in the catchment is 800 mm.
Altitude	720 m above mean sea level.
Surface area	Presently lake area is about 30 km², maximum depth of water in the lake is about 20 m, and the lake perimeter is about 24 km. The lake used to be 63 km² in area, 33 m in maximum depth, 30 m in minimum depth, and 44 km in lake perimeter in the beginning. Out of total lake area of about 63 km², there are different islands covering an area of about 15 km².
Inflow	From the catchment area
Outflow	No outflow. Loss of water is only through evaporation.
Type of lakes	Jaismond lake is one of the largest man-made freshwater lake in the world, constructed 420 years ago in A.D. 1685.
Ecological status	- Still the lake water is fresh and sweet in taste. - Profusion of aquatic vegetation and fish resources. - There is a National WildLife Park on the side of the lake. In this WildLife Park, wild animals roam about freely in their natural way.
Changes over the last years	The earthen dam was constructed in the valley of Aravalies closing all the natural outlets. Due to rapid deforestation activities in the Aravalies sediment load in the lake is increasing year by year. Hydrology of the lake catchment is also changing. The lake thus created 420 years ago has been filled by sediment deposits to its present level.
Biodiversity	- Famous for its fish catches. Fishes from Jaismond lake are famous for their tastes. Fish from this lake is exported not only to other parts of the country but in most of the European and Western Countries. - Different types of migratory birds can be seen in the lake during different seasons of the year. - Several aboriginal tribes inhabit these islands in the lake and use locally made boats to ferry to different islands. These tribes depend on lake aquatic resources for their livelihood. They still live naked and use ancient form of weapon for hunting of fishes and other wild life.
Recreation	- One of the very important tourist centers of India. People from all over the country visit Jaismond lake to see the majestic lake and enjoy boating and fishing in the lake. - There are six beautiful Chatries on the earthen dam. There is a big Shiv Temple in the lake. - On the occasion of Shiv Ratri a big fair takes place - This lake is also called Dhebar lake.
Commercial use	For fish catch and also for irrigation purpose.
Studies undertaken	No study has been undertaken by any organization in India.
Governing authority	- Rajasthan State Government - Maharana of Mewar Memorial Foundation
General	The lake was constructed for providing drinking water to the local people and at the same time to create an aesthetic environment
Lake	Salt lakes of Rajasthan
Location	Sambhar lake, Phulera lake, and Didwana lake On the border of Jodhpur and Jaipur, 64 km to the west of Jaipur city 65 km to the north west of Sambhar is Didwana lake

Indian Lakes, Table 1 (Continued)

Location on map	Sambhar lies between 27°00' N latitude and 75°00' E longitude, Phulera lake lies between 27°12' N latitude and 74°34' E longitude, and Didwana lake lies between 26°52' N latitude and 75°11' E longitude
Climate	The climate of the lake region is tropical monsoon.
Altitude	360 m above mean sea level.
Surface area	Sambhar is the largest of the three lakes having an area of 23,300 ha and length of 32 km. The area of lakes Phulera and Didwana is about 200 ha each.
Inflow	Sambhar lake is fed by seasonal rivers Bandi, Medha, and several other streams. Water level of these lakes fluctuates from few centimeters to a maximum of 2 m. Sambhar lake often dries in early summer.
Outflow	All the three lakes are surrounded by sand flats and dry throne shrubs. Thus there is no outflow from the lakes
Type of lakes	Salt lakes of Rajasthan
Commercial use	About 7,800 ha of the eastern arm of Sambhar lake is devoted for salt production while 20% of Didwana lake is used as salt pans. The saline mud in Sambhar lake is 22 m deep and is underlain by a thin white crust of glistening common salt. The sediments below are saturated with brine. It is estimated that in the upper 4 m of the mud in the lake, whose average salt content is about 6%, there would be roughly 1 million tones of salt per square meter. Sambhar lake contains practically no magnesium salts. Potassium salts are absent in Didwana lake. Sodium Sulfate is present in Sambhar and Didwana.
Lake	Lonar lake in Maharashtra, India
Location	Situated at 140 km from Aurangabad, Lonar lake is a saltwater lake at Lonar in Buldana district, Maharashtra, India
Location on map	19°58'36"N 76°30'30"E
Climate	Semiarid climate. Annual average rainfall is around 700 mm.
Altitude	A series of low hills surround the basin which is oval in shape (almost round) with circumference at top of about 8 km (5 miles). The sides of the basin rise abruptly at an angle of about 75°. At the base, the lake has a circumference of about 4.8 km (3 miles). The slopes are covered with jungle interspersed with teak tree. A belt of large trees about a mile broad runs all-round the basin; belt is formed of concentric rings of different species of trees. A ring of date palms followed by a ring of tamarind trees (nearly 1.6 km or a mile broad) leads to a ring of babul trees, bounded on the inside by a belt of bare muddy space; mud space is several hundred meters/yards broad, devoid of all vegetation (due to soda content in the water), covered with a whitish slimy soil, and leads to the lake water. During the rainy season, the drainage into the lake covers the muddy space. The water of the lake contains various salts or sodas. During the dry weather, as the water level reduces with evaporation, large quantities of sodas are collected. A well of sweet water is also located on the southern side of the lake, close to lake's water edge
Surface area	Two small streams drain into the lake. Lonar lake has a mean diameter of 1.2 km (3,900 ft) and is about 137 m (449 ft) below the crater rim. The meteor crater rim is about 1.8 km (5,900 ft) in diameter. The circular depression bears a saline water lake in its central portion.
Inflow	There is underground feeding of the lake.
Outflow	Only through evaporation.
Type of lakes	• Lonar lake is the largest and oldest natural lake of meteor origin in the world. The lake is around 50,000 years old. The rim of the lake stands 5–6 m above the surrounding country, the trap appearing to dip away from the depression. • A lake that evolved in the resulting basaltic rock formation is both saline and alkaline in nature. • Profusion of aquatic life. • The chemical characteristics of the lake show two distinct regions that do not mix – an outer neutral (pH 7) and an inner alkaline (pH 11) each with its own flora and fauna. The lake is a haven for a wide range of plant and animal life. Resident and migratory birds such as black-winged stilts, brahminy ducks, grebes, shell-ducks (European migrants), shovellers, teals, herons, red-wattled lapwings, rollers or blue jays, baya weavers, parakeet hoopoes, larks, tailorbirds, magpies and robins and swallows are found on the lake. Among reptiles, the monitor lizard is reported to be prominent. The lake is also home to thousands of peafowls, chinkara, and gazelles. Plea to declare Lonar lake a protected wetland.
Ecological status	
Changes over the last years	• Mean depth of water in the lake of the order of 100 m is left only to about 50 m due to bottom being of highly weathered trap due to continued siltation in the lake. Underground feeding of the lake is bringing pollutant into the lake.
Recreation	• Center for all religious activities in Maharashtra

Indian Lakes, Table 1 (Continued)

Studies undertaken	• Geologists, ecologists, archaeologists, naturalists, and astronomers have reported several studies on the various aspects of this crater lake ecosystem. • The crater's age is usually estimated to be $52,000 \pm 6,000$ years (Pleistocene) (Geological Survey of India & Report, 1988), although a study published in 2010 gives an age of $656,000 \pm 81,000$ years. • The Smithsonian Institution, the United States Geological Survey, Geological Society of India, and University of Sagar and the Physical Research Laboratory have conducted extensive studies about the site. • Biological nitrogen fixation has been discovered in this lake in the year 2007. Nonsymbiotic nitrogen fixing microorganisms such as <i>Halomonas</i> sp., <i>Paracoccus</i> sp., <i>Klebsiella</i> sp., <i>Slackia</i> sp., and <i>Actinopolyspora</i> sp. have been reported from this lake. All the nitrogen fixers are haloalkaliphilic in nature as they can grow only at pH-11. Some of the bacteria and actinomycetes isolated from this lake are able to grow on some components of inorganic medium containing martian soil simulant components. • Maharashtra State Government
Governing authority General	Created by a meteor hitting the Earth during the Pleistocene Epoch. The lake is said to be the only crater in the great basaltic formation of India. The lake was initially believed to be of volcanic origin, but now it is recognized as an impact crater created by the hypervelocity impact of either a comet or a meteorite. The presence of plagioclase that has been either converted into maskelynite or contains planar deformation features (PDFs) has confirmed the impact origin of this crater. It is argued that only shock metamorphism caused by hypervelocity impact can transform plagioclase into maskelynite or create PDFs. The presence of shatter cones, impact deformation of basalt layers comprising its rim, shocked breccia inside the crater, and non-volcanic ejecta blanket surrounding the crater are further proofs of the impact origin of Lonar crater. As a result of the studies, broadly, the geological features of the Lonar crater has been marked under five distinguishable zones, exhibiting distinct geomorphic characteristics. The five zones are the following: 1. The outermost ejecta blanket 2. The crater rim 3. The slopes of the crater 4. The crater basin, excluding lake 5. The crater lake
Lake Location	Vihar lake, Mumbai, Maharashtra Vihar lake is located near Vihar village on the Mithi River within the precincts of the Borivali National Park, also called the Sanjay Gandhi National Park, in North Mumbai. By road, it is 31 km from Mumbai. Access by suburban electric train is to Kurla or Andheri and then by road. Access to the lake for the general public has been curtailed since March 13, 1993 (Source: Official BMC Board installed at the gate) following the Bombay Bombs on March 12, 1993 due to perceived threats to the Mumbai public, as the lake is located in the Sanjay Gandhi National Park.
Inflow	Impoundment of Mithi River, 20 km north of Mumbai, was effected to store the rainwater from a catchment area of 18.96 km^2 to create the Vihar lake. The Powai-Kanheri hill ranges form the catchment area, which drains the rainwater into the lake. For this purpose, three earthen embankment dams with a masonry spillway section were constructed to create a reservoir of 9,200 million gallons capacity at the full reservoir level of 80.42 m. The lake has a maximum water depth of 34 m and a minimum of 12 m. The lake's water spread area is 7 km^2. The dam height was raised in 1872 resulting in increase of water supply from 32 million gallons (catering to a population of 0.7 million) to 36 million gallons.
Biodiversity	Flora and fauna Mugger or Marsh Crocodile The lake and its catchment are protected by the Brihanmumbai Municipal Corporation and Sanjay Gandhi National Park Authority. The catchment areas of Vihar lake has high hills rising on all sides. The seclusion, protection, and security provided under the Sanjay Gandhi National Park have ensured well-wooded hill slopes and abundant natural regeneration. Higher percentage of khair species has been noted in the catchment area of the lake. As the lake is situated inside the Sanjay Gandhi National Park, the flora and fauna reported for the park would be relevant to the lake. However, freshwater crocodiles, Mugger or Marsh crocodiles (<i>Crocodilus palustris</i>), are known to inhabit the lake in sustainable numbers. As it is difficult to sight them in the lake, the park has set up a Crocodile Park to view the reptiles of different sizes.

Indian Lakes, Table 1 (Continued)

Commercial use	When built in 1860 (construction started in 1856), it was considered as the largest lake in Mumbai in the Salsette group of islands. It is hemmed between the Tulsi lake and the Powai lake (shown in map). It partly meets the drinking water needs of the South Mumbai region. It supplies only 3% of the Mumbai city's water requirement, after filtration at Bhandup where the large water filtration plant is located.
Studies undertaken	Limnological studies carried out by the Central Public Health Engineering Research Institute, Nagpur, India in 1964 indicated an unstable thermal stratification in the lake waters. The dissolved oxygen (DO) values were found to increase in some months and carbon dioxide was found to be less at the surface than at the bottom. In cooler season, the surface water was found to be less alkaline, which could be attributed to the photosynthesis activity of the algae. The pH stratification was found to be unstable. Interrelation was attributed to fluctuations in the chlorophyll, pH, and DO values; nitrates were generally absent on the surface and no sulfates were detected. Mahim Creek where Mithi River joins and where the sweet water episode occurred in 2006. In the year 2006, finding sweet water at the Mahim Creek (a semi-enclosed area), where freshwater and seawater meet, created a lot of excitement among the public. The health department of BMC who analyzed the water sample from the site found that salt level in the seawater was as low as 600 particles per million (ppm), compared to the normal level of 10,000 ppm. The National Institute of Oceanography, Goa, who were also consulted, stated that this phenomenon was not unusual and could have been caused by heavy rainfall and low tide. This necessitated the Maharashtra Government to intervene and examine the issue rationally to convince the excited public. BMC Commissioner gave a press statement stating: "The Mahim creek is located in a semi-enclosed area where freshwater and seawater mix especially during low tide, which caused the dilution. Also, the Vihar lake on the outskirts of Mumbai has been overflowing for the past few days and has flown into the Mithi River, which could be the reason for the water tasting sweet."
Governing authority General	The Brihanmumbai Municipal Corporation (BMC), a Government body With the few thousand wells feeding the population of Mumbai tending to go dry during summer, the acute shortage of water resulted in protests by the local residents in June 1845. A two-man committee, appointed by the British rulers of the time, to examine the grievances of the agitators concurred with water shortage problem and stressed the urgent need to solve the water supply problem of Mumbai. The Committee appointed by the government located suitable sites to construct dams and create reservoirs to store the monsoon flows of the Mithi river catchment, which resulted in the presently existing Vihar lake, Tulsi lake, and the Powai lake. Vihar reservoir was the first piped water supply scheme of Mumbai. In 1850, Captain Crawford submitted a report favoring the Vihar Scheme for the Mumbai city's water supply needs. Work on the "Vihar Water Works" commenced in January 1856 and was completed in 1860, during the governorship of John Lord Elphinstone (Cavazza, 1993). The Brihanmumbai Municipal Corporation (BMC) which controls the lake's affairs has also acquired agricultural land in the catchment area of the Vihar lake as a sanitary precaution.
Lake	Tulsi lake, Mumbai, Maharashtra
Location	Tulsi lake is in northern Mumbai, 32 km to the north of Mumbai by road. The nearest suburban electric train station is Borivli East on the Western Railways and is close to western express highway, with a further travel of 6 km from the station by road to the lake. The nearest Sahar International Airport is at a distance of about 20 km. As the lake is located inside the Sanjay Gandhi National Park, entry permits are to be obtained from the park authorities for visit to the lake. This is one of the three lakes located in the Salsette Island; the other two being Powai lake and Vihar lake. Both Tulsi lake and Vihar lake are located within the densely forested Sanjay Gandhi National Park or also known popularly as the Borivali National Park (BNP).
Location on map	19° 11' 24" N 72° 55' 04" E 19.1901° N 72.9179° E
Climate	The southwest monsoon sets in by mid-June and lasts till September. The maximum rainfall is normally recorded in the months of July and August. The mean annual rainfall is reported to be 2,500 mm.
Altitude	139.17 m above mean sea level
Surface area	Surface area of the lake is 1.355 km ² whereas the catchment area of the lake is 6.75 km ² . Average depth is 12 m with a gross storage at Full Supply Level (FSL) of 2,294 million gallons, out of which four million gallons per day are supplied to Greater Mumbai. The highest overflow level, recorded at the dam is 139.17 m (456.6 ft). This freshwater lake primarily fulfills the water requirement of the southern part of Mumbai.

Indian Lakes, Table 1 (Continued)

Inflow	Tulsi lake was built by damming the River Tasso, and redirecting the flow to the nearby Vihar lake. Rainwater from the catchment area of 676 ha of Powai-Kanheri hill ranges drains into the lake.
Outflow	During rainy season the flood flows into the Powai lake and further down in to the Mithi River.
Type of lakes	A freshwater lake
Ecological status	The vegetation on the hill slopes draining into the lake is thick and lush, undisturbed, and of mixed moist deciduous type.
Biodiversity	As the lake is situated inside the Sanjay Gandhi National Park, the flora and fauna reported for the park would be relevant to the lake. However, freshwater crocodiles, Mugger or Marsh crocodiles (<i>Crocodilus palustris</i>), are known to inhabit the lake in sustainable numbers. As it is difficult to sight them in the lake, the park has set up a Crocodile Park to view the reptiles of different sizes.
Recreation	For tourists.
Commercial use	It is stated to be the second largest lake in Mumbai and supplies part of the city's potable water.
Governing authority	The lake and its catchment are protected by the Brihanmumbai Municipal Corporation and Sanjay Gandhi National Park Authority.
Lake	Powai lake, Mumbai, Maharashtra
Location	Powai lake (named after Framaji Kavasji Powai Estate) is situated in the northern suburb of Mumbai, in the Powai valley, where a Powai village with cluster of huts existed. Powai lake is located downstream of the Vihar lake on the Mithi River.
Location on map	19°08'N 72°55'E/19.13°N 72.91°E
Altitude	58.5 m
Surface area	Catchment area is 6.61 km ² .
Type of lakes	An artificial lake
Changes over the last years	The city suburb called Powai shares its name with the lake. Indian Institute of Technology, Bombay, one of the premier institutions of science and technology in India, is located to the east of the lake. Another famous institution, the National Institute of Industrial Engineering (NITIE) is also located close to the lake. Housing complexes and plush hotels are developed all around the lake periphery. Population around the lake has thus substantially increased over the years. When it was built, the lake had a water spread area of about 2.1 km ² (520 acres) and the depth varied from about 3 m (9.8 ft) (at the periphery) to 12 m (39 ft) at its deepest. The Powai lake has gone through many stages of water quality degradation. The lake water which used to supply to Mumbai for drinking water has been declared unfit to drink. The lake still remains a tourist attraction.
Lakes of Eastern India	
Lake	Chilka lake in Orissa, India
Location	Situated at 150 km south west of Cuttack, Orissa, India
Location on map	19°43'N 85°19'E/19.717°N
Climate	A tropical monsoon climate prevails over the drainage basin area of the lake. The lake experiences Southwest and Northeast monsoons during June to September and November to December, respectively, with average annual rainfall of 1,238.8 mm (48.77 in.), with 72 rainy days. The maximum temperature of 39.9°C (103.8°F) and minimum temperature of 14°C (57.2°F) have been recorded. The wind speed varies from 5.3 to 16 m (17–52 ft)/h with southerly and southwesterly direction due to the influence of the Southwest monsoon and from north and north easterly direction during the rest of the months.
Altitude	0–5 m. above mean sea level
Surface area	Maximum area of the lake is 1,165 km ² (450 miles ²) and minimum area of the lake is about 740 km ² (286 miles ²). Catchment area of the lake is 3,560 km ² (1,370 miles ²). Maximum depth is 4.2 m (13.8 ft), water volume is 4 km ³ (3,200,000 acre·ft), and surface elevation is 0–2 m (6.6 ft).
Inflow	35 streams including the Bhargavi, Daya, Makra, Malguni, and Nuna rivers' inflow rate of the silt into the lake is about 13 million tones per year. Water volume is 4 km ³ (3,200,000 acre·ft).
Outflow	Old mouth at Arakhakuda, new mouth at Satapada to Bay of Bengal
Type of lakes	Large, shallow, pear-shaped, brackish natural lake, separated from Bay of Bengal by a 200-m high sandy ridge which is 71-km long and 32-km wide.
Ecological status	The lake has numerous islands. The larger islands, separated by shallow channels, lie between the barrier and the main body of the lake. A total 42 km ² (16.2 miles ²) of channels connect the lake with Bay of Bengal. The six major islands are Parikud, Phulbari, Berahpura, Nuapara, Nalbana, and Tampara. These islands, together with the peninsula of Malud, constitute the Krishnaprasad Revenue Block of Puri District.

Indian Lakes, Table 1 (Continued)

Changes over the last years	• Due to siltation the width of the barrier has fluctuated and the mouth to the sea has periodically been closed. The location of the mouth has also frequently shifted, generally toward the northeast. The mouth, which was 1.5 km (0.9 miles) wide in 1780, was only 75 km (0.5 miles) 40 years later. The local fisherfolk, to maintain their livelihood, had to cut open the mouth regularly to gain access to the sea for fishing. • The lake is shrinking due to shore area of the lake being reclaimed for prawn effluents. • Inflow rate of the silt into the lake is about 13 million tonnes per year due to which the lake is shrinking.
Biodiversity	• Chilika lake is the largest wintering ground for migratory birds, on the Indian subcontinent. It is one of the hot spots of biodiversity in the country. Some species listed in the IUCN Red List of threatened animals inhabit the lake for at least part of their life cycle, which are white bellied sea eagles, greylag geese, purple moorhen, jacana, herons and flamingos, Egrets, Gray and Purple Herons, Indian Roller, Storks and White Ibis, Spoonbills, Brahminy Ducks, Shovellers and Pintails, and more. Migratory waterfowl arrive here from as far as the Caspian Sea, Baikal lake, and remote parts of Russia, Mongolia, Lakah, Siberia, Iran, Iraq, Afghanistan, and from the Himalayas. A census conducted in the winter of 1997–1998 recorded about two million birds in the lake. • Other than the birds, Chilka's shores are home to blackbuck, spotted deer, golden jackals, and hyenas, and the lake is rich in aquatic life – its waters harbor around 160 species of fish, crustaceans and other marine creatures, including the famous Chilka dolphin. Prawn, crab, and mackerel fishing are an important source of livelihood for the local people, and hundreds of small fishing boats set sail each morning to bring in the day's catch from the lake. The Nilgiri Biosphere Reserve harbors India's second largest pachyderm population, and the chances of seeing elephant herds is pretty high, especially during the dry season.
Recreation	The lake was declared the wetland of international importance in 1981 under the Ramsar Convention. Lots of migrating birds visit Chilka every year. Chilka bird sanctuary has been established.
Commercial use	The lake is used mainly for fishing.
Studies undertaken	Limnological and ecological studies
Governing authority	Chilka Lake Development Authority
General	• The Chilka lake in Orissa is Asia's largest inland saltwater lagoon. Studded with small islands – including the picturesquely named Honeymoon Island and Breakfast Island – the lake is separated from the Bay of Bengal by a sandy ridge. The pear-shaped lake spreads across 1,100 km² and has a unique ecosystem with a range of aquatic flora and fauna found in and around its brackish waters. An impressive array of bird life, both native and migrant, makes Chilka one of the best places in India for a bit of satisfying bird-watching. White bellied sea eagles, greylag geese, purple moorhen, jacana, herons, and flamingos are among the many species which make the lake a bird watcher's delight: Chilka, in fact, is home to one of the world's largest breeding colonies of flamingos. • Chilika lake is a shallow bar built estuary with huge areas of mudflats. The western and southern margins of the lake are fringed by the Eastern Ghats hill range. • Several inland rivers, which bring silt into the lake, control the northern end of the lake. A 60-km (37 miles) long barrier beach called Rejhansa, formed by northerly currents in the Bay of Bengal resulted in the formation of this shallow lake and forms its eastern side. As an ephemeral lake its water surface area varies from 1,165 km² (449.8 miles²) in the summer monsoon season to 906 km² (349.8 miles²) in the winter dry season. • The mean depth of water in the lake varies from 0.9 to 2.6 m in dry season and 1.8 to 3.7 m in monsoon season.
Lake	Rabindra Sarobar, Kolkata, West Bengal
Location	Rabindra Sarobar (previously known as Dhakuria lake) is in south Kolkata in the Indian state of West Bengal. It is popularly referred to as the "Lungs of Calcutta." The name also refers to the area surrounding the lake. It is flanked by Southern Avenue to the North, Russa Road to the West, Dhakuria to the East, and the Kolkata Suburban Railway tracks to the South. Rabindra Sarovar is 30 km away from Dum Dum airport and 12 km from the Howrah railway station. The area is served by the Rabindra Sarobar station of the Kolkata Metro and lake Gardens and the Tollygunge station of the Kolkata suburban railway (Budge Budge section). It is one of the two points where the two railway systems interface (the other being Dum Dum).
Surface area	73 acres (300,000 m ²) are covered by water, while shrubs and trees, some of which are more than 100 years old, occupy the rest of the area.
Type of lakes	It is an artificial lake.

Indian Lakes, Table 1 (Continued)

Changes over the last years	Like a majority of artificial lakes in the country, Rabindra Sarovar is suffering environmental degradation. Water pollution is on the rise, owing to an increase in tourist flow and habitation around the lake. The Ministry of Environment and Forests, Government of India, has recently included this lake under the National Lake Conservation Plan in the hope that this will help preserve it. The local authorities have also begun an extensive tree plantation program.
Biodiversity	In the winter, one can spot some migratory birds around the lake, though the numbers are dwindling because of the rise in pollution level. The lake itself is home to many varieties of fish. Fishing is strictly prohibited.
Recreation	Today the lake and its surrounding areas are one of the most popular recreational areas in Kolkata. The area around this excavated lake was later developed to build recreational complexes, which included children's parks, gardens, and auditoria. A number of people come for a walk around the lake in the mornings to enjoy the fresh air. Many visit the sunrise point to offer their prayers to the Sun. During the day, it is visited by families on a picnic, tourists, young lovers, and joggers.
Commercial use	There is an auditorium or a hall within the sarovar complex which adjoins the Rabindra Sarovar Stadium. Its name is Pavilion Hall. A number of rowing and swimming clubs are situated within the Rabindra Sarovar complex. While the former are located to the north of this lake, the latter are located to its south. In 1858, the British founded the Calcutta Rowing Club (CRC), presently one of the oldest clubs in India, to promote rowing activities in Kolkata. In 1901, it got affiliated to the prestigious Amateur Rowing Association of the East (ARAE) and in 1923 signed a reciprocal arrangement deal with the London Rowing Club. The CRC has been the hub of competitive rowing in Kolkata for more than 150 years and has organized many intra- and inter-club competitions. Rowing facilities are available to members on a regular basis, from 6 a.m. to 7:30 a.m. and from 3:30 p.m. to 5 p.m. The Bengal Rowing Club, Lake Club, and Calcutta University Rowing Club are a few other rowing clubs located in the Rabindra Sarovar complex. One of the most prestigious and oldest swimming clubs in Kolkata, the Indian Life Saving Society (formerly known as Anderson Club) has its office in the lake complex.
Governing authority	Calcutta Improvement Trust (CIT)
General	In the early 1920s, the Calcutta Improvement Trust (CIT), a body responsible for developmental work in the Kolkata metropolitan area, acquired about 192 acres (0.78 km ²) of marshy jungles. Their intention was to develop the area for residential use – improving the roads, raising and leveling some of the adjacent land, and building lakes and parks. Excavation work was undertaken with the plan of creating a huge lake. Originally known as Dhakuria lake, in May 1958, CIT renamed the lake as Rabindra Sarovar, as a tribute to the great Bengali writer and Nobel Laureate, Rabindranath Tagore. Like a majority of artificial lakes in the country, Rabindra Sarovar is suffering environmental degradation. Water pollution is on the rise, owing to an increase in tourist flow and habitation around the lake. The Ministry of Environment and Forests, Government of India, has recently included this lake under the National Lake Conservation Plan in the hope that this will help preserve it. The local authorities have also begun an extensive tree plantation program.
Lakes of North-Eastern India	
Lake	Loktak lake in Manipur
Location	Near Moirang in Manipur state, India.
Location on map	24°33'N 93°47'E
Climate	Tropical Monsoon Climate. With an average annual rainfall of 1,183 mm (46.57 in.) tropical monsoon climate prevails in the valley. Temperatures range from 0°C to 35°C (32–95°F). February and March are the driest months.
Altitude	770 m above mean sea level
Surface area	Surface area 287 km ² (111 miles ²) Max. length 35 km (22 miles) Max. width 13 km (8 miles) Average depth 2.7 m (8.9 ft) Max. depth 4.6 m (15.1 ft) Surface elevation 768.5 m (2,521 ft)
Inflow	The river Loktak and its tributaries, which flowed at much lower level in the past, were dammed when an earthquake raised a barrier and closed its outlet. The lake thus created was filled with alluvia to its present level, leaving the lake in its part. The lake is connected to Imphal River by a 10-km long natural course known as Khordak Cut. Water exchange between the lake and Imphal river takes place depending upon water level of the lake and river.
Outflow	Runoff from the surrounding hill from three sides feed the lake. Ungamel Channel (Ithai Barrage) is its only outlet now. Through barrage for hydropower generation, irrigation, and water supply

Indian Lakes, Table 1 (Continued)

Type of lakes	The largest freshwater lake in northeastern India, also called the only Floating lake in the world due to the floating phumdis (heterogeneous mass of vegetation, soil, and organic matters at various stages of decomposition) on it
Ecological status	During non-rainy season, inflow to the lake brings domestic sewage, fertilizers, and pesticides. Due to eutrophication and siltation, vast portion of the lake has been covered by thick algae locally called Phumdi due to which power production from the lake is suffering. Profusion of aquatic vegetation. Famous for its floating mass called phumdi. Phumdi in the lake being the only refuge of the endangered Sangai (meaning “the one that looks at you”), Manipur brow-antlered deer (the most endangered species in the wild), Hog Deer, Common Otter, Large Indian Civett, Small Indian Civett, and Indian Wild Bear.
Changes over the last years	Maximum depth of water in the lake is about 20 m and minimum depth of water in some part of the lake is about 5 m. The lake is shrinking fast. Maximum depth of lake has reduced from 29 m in 1950 to about 20 m in 1980. It had vast area of 2,000 km ² in 1950 that reduced to 495 km ² in 1971 and 289 km ² in 1995.
Biodiversity	Encroachment is also for reclamation of land for agriculture, socioeconomic activity. It is a wetland of international importance included in RAMASAR Convention. • The enormous quantities of vegetable matters decaying in the swamps make them high capacity fertilizer factories releasing large quantities of fish food. • About 172 macrophytes species – 14 floating, 15 submerged, 5 rooted floating, 25 shallow water species, 25 habitats in the marginal areas, and 65 composing the phumdi. • Migrating waterfowl. Enormous flocks of ducks and geese. Of the 51 species recorded in recent times, migratory birds constitute about 24%. Several species of migratory birds also bypass Loktak as a wintering area. • Designated as “Jewel of Switzerland” of India due to its biological richness and uniqueness of habitat.
Commercial use	• The lake is the lifeline of Manipur Valley. The lake is used for domestic purpose, irrigation, power generation, fishing, and navigation. The Loktak Hydroelectric Project is running by constructing Ithai Barrage on the Khordak Cut. There is a hydropower plant of 10 MW being operated by lake water. Lake area is about 26,000 ha. • Enormous fish resources support large fishing communities in and around the lake area. About 60% of the fish catch of Manipur comes from Loktak alone. • Tourist inflow is mostly from East Asian Countries due to its proximity to East Asia. • This ancient lake plays an important role in the economy of Manipur. It serves as a source of water for hydropower generation, irrigation, and drinking water supply. The lake is also a source of livelihood for the rural fisherman who live in the surrounding areas and on phumdis, also known as “phumshongs.” Human activity has led to severe pressure on the lake ecosystem. Fifty-five rural and urban hamlets around the lake have a population of about 100,000 people.
Studies undertaken	• Limnological study by Manipur University • Preliminary field investigation for hydrological study by National Institute of Hydrology, Roorkee
Governing authority	• Manipur State Government • Loktak Lake Development Authority • WWF (World Wild Fund) is also active for the lake
General	Serious threat from pollution and encroachment. Considering the ecological status and its biodiversity values, the lake was initially designated as a wetland of international importance under the Ramsar Convention on March 23, 1990. But the lake was designated by the Ramsar Convention under the Montreux Record on June 16, 1993, for the reason of keeping a record of Ramsar sites where changes in ecological character have occurred, are occurring or are likely to occur.
Lake	Deepar Beel in Assam
Location	Situated at a distance of 10 km southwest to Guwahati, Assam, India
Location on map	26.13°N 91.66°E
Climate	Tropical humid monsoon climate with annual average rainfall of 1,800 mm. Temperatures in the beel vary from 10°C to 32°C. During the winter months, when the size of the lake reduces in area by about 50%, the shore area (up to 1 km) is cultivated with rice paddy when the climate is also relatively cool and dry. The tropical monsoon climate prolongs from May to September when it is humid. Pre-monsoon showers are experienced between March and May.
Altitude	53 m above mean sea level
Surface area	Lake area is about 4,000 ha. Depth of water at maximum flooding is about 4 m which drops down to 1 m in dry season. The Beel has a perennial water spread area of about 10.1 km ² , which extends up to 40.1 km ² during floods. However, an area of 414 ha has been declared as “Deepor Beel Sanctuary” by the Government of Assam. As per a Remote Sensing Study the wetland area is reported to have reduced to 14.1% (405 ha) from 1990 to 2002.

Indian Lakes, Table 1 (Continued)

Inflow	The Basistha and Kalmani rivers and local monsoon runoff are the main sources of water to the lake, between May and September. Khonajan channel drains the beel into the Brahmaputra river, 5 km to the north. It acts as a natural stormwater reservoir during the monsoon season for the Guwahati city (stated to be the only major storage water basin for the city's drainage, with about 4 m depth of water during monsoon dropping to about 1 m during the dry season.
Outflow	To river Brahmaputra
Type of lakes	A natural freshwater lake
Ecological status	The hydrophytic vegetation of the beel has been classified, based on ecological adaptation, into the following categories with their floristic elements (MAPCOST Report, 1996): Aquatic vegetation like water hyacinth, aquatic grasses, water lilies, and other submerged, emergent, and floating vegetation are found during the summer season. In the dry areas, during winter, aquatic and semi-aquatic vegetation are seen. In deep open water area, marshy lands, mud flat, emergent vegetation, water hyacinth patches, and net-grass land patches are reported. Migratory waterfowl, residential waterfowl, and terrestrial avifauna are common in paddy field areas, dry grassland areas, and scattered forest areas. A total of 18 genera of phytoplankton are reported from the core area of the Beel ecosystem out of which species of <i>Oscillatoria</i> and <i>Microcystis</i> are dominant.
Changes over the last years	Half of the lake dries in winter and the shore line is converted to rice fields. Due to this there is continuous encroachment by the farmers resulting in shrinkage of the lake. Forest to the south of the lake is being felled due to which heavy sediment load is coming into the lake resulting in its shrinkage. Natural and anthropogenic causes for the deterioration of the beel are many. The major reasons reported in the beel ecosystem are the following: • Proliferation of human settlements, roads, and industries around the periphery (in the eastern and northeastern sides) causing pollution problems • Wastewater from different parts of the city and the adjoining areas • Construction of broad-gauge railway line on the periphery of the beel • Allotment of the government vacant land to private party by Government settlement department • Brick kilns and soil cutting • Hunting, trapping, and killing of wild birds and mammals • Unplanned intensive fishing practices (both during day and night)
Biodiversity	The beel is a natural habitat to many varieties of birds. Birds of 219 species including more than 70 migratory species are reported in the beel area. The largest congregations of aquatic birds can be seen, particularly in winter, with a reported recorded count of 19,000 water birds in a day. Some of the globally threatened species of birds are Spot-billed Pelican (<i>Pelecanus philippensis</i>), Lesser Adjutant Stork (<i>Leptoptilos javanicus</i>), Baer's Pochard (<i>Aythya baeri</i>), Pallas' Sea Eagle (<i>Haliaeetus leucogaster</i>), Greater Adjutant Stork (<i>Leptoptilos dubius</i>), etc. Surveys have revealed 20 amphibians, 12 lizards, 18 snakes, and 6 turtle and tortoise species in the beel. Over 50 commercially viable species of fish belonging to 19 families have been identified, which supplies stock to other nearby wetlands and rivers. The beel provides food, acts as a spawning and nursery water body; some of the species breed within the beel. Spot-billed pelican found in beels and lakes in India. Among the large number of migratory waterfowl, the Siberian crane (<i>Grus leucogeranus</i>) regularly migrates to this habitat during its annual journey. This is in addition to the large congregation of residential water birds seen in the lake.
Commercial use	Considering the richness of the bird varieties found in the beel, the Birdlife International has declared Deepor Beel as an Important Bird Area (IBA) with high priority for conservation. The inhabitants around the villages located in the periphery and the catchment of the beel use the beel for the following: • Fishing • As waterway for transporting the villagers of the southern boundary to the NH 37 • Collecting fodder for domestic cattle and collecting aquatic seeds such as Giant water lily, <i>Nymphaea</i> sp., etc. • Raising Boro paddy – sown in December–January and harvested during April–May

Indian Lakes, Table 1 (Continued)

Studies undertaken	The Ramsar Convention, which has recognized the Deepor Beel in its list of 1,782 wetland sites, with 158 Contracting Parties to the Convention of the world and holds seminars to create awareness of the beel's uniqueness. Aaranyak, an NGO organization set up to foster conservation of biodiversity in Northeast India through research, environmental education, capacity building, and advocacy for legal and policy reforms to usher a new era of ecological security is actively involved in Community Based Conservation Projects, which include among other projects the "Deepor Beel Community Conservation Project." The project was designed to reduce the anthropogenic pressure on the wetland by providing for alternative and diversified means of livelihood to the people living along the fringe villages. The purpose of the project is to set up some community run "Self-Help Groups" (SHGs) to strengthen their livelihood options through diverse means and gain their support in the conservation of Deepor Beel as wetland ecosystem. North Dakota State University, USA, has a website created as a tool to facilitate better understanding of the concepts and practices in environmental management, and to complement the graduate course materials for the students who undertook a "Case Study of Deepor Beel Wetland Management" for the fall course of 2007. The Animal Ecology Laboratory in the Department of Zoology, Guwahati University has been involved in biological studies of the beel.
Governing authority	• Deepar Beel Bachao Samiti. • Fisheries Department, Government of Assam, India
General	<i>Guwahati Water Bodies (Preservation and Conservation) Bill, 2008</i> Due to serious threat from pollution and encroachment, The Guwahati Water bodies (Preservation and Conservation) Bill, 2008 has been passed with the objective of preserving the wetland, minimizing the problem of waterlogging in the city and creating an eco-friendly atmosphere. With this Bill at its command, the Government of Assam is planning to reacquire land in the periphery of Deepor Beel, to undertake development projects, including water sports at the beel, and for this purpose a budgetary allocation of about US\$3 million (Rs.12 crores) has been approved.
Lake	Rudrasagar (Lake) in Tripura, India
Location	Situated 55 km west of City of Agradala in Tripura, India
Location on map	23.13°N 90.66°E
Climate	Tropical humid monsoon climate with annual average rainfall of 2,500 mm, with 4/5 flood peaks. The tropical monsoon climate prolongs from May to September when it is humid. Pre-monsoon showers are experienced between March and May. Temperature variation in and around the lake is from 37°C to 50°C.
Altitude	53 m above mean sea level
Surface area	About 6 km ² , maximum depth of water in the lake is about 6 m. Lake water is fresh with insignificant pollution with a depth varying from 2 m to 9 m. Fluctuation in water level varies from EL 9 m to 16 m.
Inflow	The lake receives flow from three perennial streams, namely, Noacherra, Durlavnaraya cherra, and Kemtali cherra. Substantial base flow in streams around the year.
Outflow	After settling the sediment from the received flow, clear water discharges into the River Gomati through a connective channel, namely, Kachigang. Lake outflow is controlled by sluice gates.
Type of lakes	Hydromorphologically, Rudrasagar lake is a natural sedimentation reservoir. The lake bed has been formed by silt deposition. As such no rock formation is found with 50 m being silt (Clay loam) deposition and below formation is sandy. Surrounding hillocks are of soft sedimentary formation. The soil in lake area is silty clay loam to clay loam.
Ecological status	Input to the lake is monsoon runoff from the catchment area bringing debris from the urban land and sediment from exposed agricultural field. • Night soils and other sewage from Agartala is dumped into Rudrasagar. These wastes provide biomass which is helpful for the fish population. • More than 200 macrophytes species • Profusion of aquatic vegetation
Changes over the last years	Water spread area of the lake has reduced to about 6 km ² from 12 km ² in 1950. Maximum depth of water has reduced to 6 m from 20 m in 1950. The lake and its catchment area of the lake has been encroached by planners and developers.
Biodiversity	• Migrating waterfowl. Enormous flocks of ducks and geese. • Several species of migratory birds mostly from eastern countries bypass Rudrasagar lake during different seasons of the year. Enormous fish resources support large fishing communities in and around the lake area. About 50% of the fish catch of Tripura comes from Rudrasagar alone.

Indian Lakes, Table 1 (Continued)

Recreation	In 1980, the erstwhile King of Tripura, Bir Bikram Kishore Manikya Bahadur built a magnificent water palace in the midst of Rudrasagar lake, called Neermahal. It served as his summer residence. It is Northeast India's only water palace. This palace "Neer Mahal" is similar to "Lake Palace" in Pichola lake at Udaipur. Basement of Neer Mahal was under water, but it now stands exposed to open air.
Commercial use	Lake water is used for fishing, recreation, tourism, and irrigation. • A palace, "Neer Mahal," was constructed inside Rudrasagar by ruling king during the eighteenth century. This palace "Neer Mahal" is similar to "Lake Palace" in Pichola lake at Udaipur. Basement of Neer Mahal was under water, but it now stands exposed to open air. • Major fairs are held on the bank of this lake.
Studies undertaken	Though pollution and encroachment is threatening the lake, no hydrological study has been taken on this lake.
Governing authority	• Fishery Department, Kunjvan, Agartala • Tripura University, Surjamani Nagar • Rudrasagar Udbastu Fisherman Samanayvay Samiti Ltd., Melaghar, Rajghat
General	The lake has faced the problem of pollution due to the following reasons: • The non-point sources of pollutant such as agricultural runoff, anthropogenic introduced solid and semisolid pollutants • Malpractices such as anthropogenic dumped garbage, deposition of solid waste and construction materials along the shoreline, etc. • Eutrophication, an uncontrolled growth of alien invasive species such as water hyacinth, excessive algae was observed in the lake which caused loss of aquatic biodiversity • Agricultural activity (use of pesticides and fertilizers) in the area adjacent to the lake • Deforestation, filling, draining and degradation of wetland areas: Clearing and removal of native vegetation due to the rapid unplanned urbanization, rural or industrial development • Lack of awareness, scientific knowledge and negligence in protection by law • Competition for using lake water such as for drinking, irrigation, fishing, etc. • Untreated or inadequately treated domestic and industrial effluents from point sources located all over the basin. • Cultural siltation in the form of immersion of idols during specific festivals, an annual feature in India, has been a source of serious metallic pollution of lakes. • Not having a definite Wetland Authority, Special Purpose Vehicles (SPVs) for Lake Management and conservation with a unified mandate have not been set up. • Lack of community toilet facilities around periphery of the lake. Ownership and legal status of the lake and the inhabitants around the lake are not clearly defined. Major soil erosion in catchment area of the lake is one of the major problems to decrease the lake area and to decrease the depth of the lake also. Such degradation in catchment area and siltation in the lake has the effect since long time in the lake. For such reason and others, the area of Rudrasagar lake has been decreased drastically from 1,000 ha prior to 1950 to more or less 100 ha at present. Silting of lakes on account of increased erosion as a result of expansion of urban and agricultural areas, deforestation, flood, immersion of idols by the religious activity and such other land disturbances taking place in the drainage basin of the lake. The Government of India's Ministry of Environment and Forest has identified Rudrasagar as one of the wetlands of National Importance for conservation and sustainable use based on its biodiversity and socioeconomic importance. Secretary General, convention on wetlands, Ramasar site has declared Rudrasagar lake as wetland of international importance and it has been included in the list of wetlands of International Importance.
Lake	Barapani lake, Meghalaya
Location	Umiyam lake, also known as Barapani (Big Water) is a spot around 15 km from Shillong where a massive hydroelectric dam has been constructed across the Umiyam river stream.
Location on map	
Climate	Temperature in summer varies from 15°C to 30°C, and in winter from 4°C to 24°C. Average annual rainfall is around 2,000 mm.
Altitude	1,525 m above mean sea level.
Recreation	The lake is popular for Water Sport and adventure facilities that it offers. Kayaking, Water cycling/scooting, and boating are a few of the facilities available at the Umiyam lake. The lake has been developed as a tourist spot by the State authorities and the Meghalaya Tourism Department runs the Orchid Tourist home overlooking the lake.
Governing authority	Government of Meghalaya

Indian Lakes, Table 1 (Continued)

General	Shillong, the capital of Meghalaya takes its name from the deity Shyllong or Lei Shyllong. This city used to be the capital of Assam for over century since 1874 till Meghalaya became a separate state. The city is based on an elevated swath which lays almost 1,500 m above the sea level. The city is picturesquely located within the Umiang ravine from north and the Diengiei hills from the northwest making this city a prey to natural blessings as well as vagaries (incessant rains during June–September). One such incident almost wiped out Shillong from the face of earth in 1897 when a strong earthquake destroyed the city. The hard working people of Meghalaya reconstructed the city completely. Shillong was born in the laps of nature and offers every one of its bequeathed element for exploration to the wanderlust. The amazing series of waterfalls, the mystic mountain peaks, crystal clear water lakes, breathtakingly beautiful golf courses, museums, and zoo; Shillong has a different façade for everyone. Though the weather Gods remain aloof during peak winters and summers, the region offers its best face in March, April, September, and October not necessarily in that sequence.
Lakes in Central India	
Lake	Upper Bhopal lake in Madhya Pradesh
Location	The largest artificial lake in Asia which lies on the Western side of the capital city of Madhya Pradesh, Bhopal, India
Location on map	23.25°N 77.34°E
Climate	Semiarid climate. Annual average rainfall in the catchment area is about 1,100 mm.
Altitude	508 m above mean sea level.
Surface area	Presently lake area is about 36 km ² , maximum depth of water in the lake is about 10 m, and minimum depth of water in the lake is about 3 m. In dry season, the lake water surface area even reduces to 5 km ² .
Inflow	Catchment area is 361 km². • From river Kolans. • During rainy season, inflow to the lake brings domestic sewage, fertilizers, and pesticides into the lake. • Due to dense population on the fringe area of the lake non-point source of pollution brings domestic sewage, industrial wastes into the lake throughout the year.
Outflow	Lake is connected to Betwa River by a minor river Kalisot into which the spillway from the lake is discharged. Overflow from the lake is controlled by 11 numbers of spillway gates.
Type of lakes	A man made freshwater lake, constructed 1,100 years ago. The lake was built by damming of river Kolans between Shyamla Hills by constructing earthen dam.
Ecological status	The Upper Bhopal lake has been declared Wetland of International Importance and included in RAMSAR Convention.
Changes over the last years	• The lake is shrinking at a fast pace. It had vast area of 1,800 km² spread up to Bhojpur at the time of construction 1,100 years ago. Mughal emperors reclaimed most parts of the lake for agriculture by putting earthen dam at Kamla Park. Lake area of about 195 km² in 1671 has got reduced to just about 30 km² by the year 2000. • It was once a vast lake that has been filled by clay sediment deposits. The present lake and associated water bodies are remnants.
Biodiversity	• “Van Vihar,” an open wild animal zoo is on the fringe of the Upper Bhopal Lake supporting wildlife. • Profusion of aquatic vegetation. • Famous for its deep-rooted tall aquatic plants which are uprooted and used by local populace for fuel requirement. • About 52 macrophyte species – 4 floating, 25 submerged, 23 deep rooted. Aquatic vegetation is shown in the photographs. • In recent times, migratory birds constitute about 54%. Of the bird population several species of migratory birds also bypass Upper Bhopal lake as a wintering area. • The enormous quantities of vegetable matters decaying in the swamps make them high capacity fertilizer factories releasing large quantities of fish food. • Enormous fish resources support large fishing communities in and around the lake area. About 70% of the fish requirement of City of Bhopal is fulfilled by catch of fish from the Upper Bhopal lake.
Recreation	• Encroachment is for reclamation of land for agriculture, socioeconomic activity, and urban development. Major encroachment in the water surface area of the lake is by the state government for creating transport facilities for VIP, recreational activities, etc. Now the local government authority is the major encroacher for creating several facilities. They are moving inward for constructing infrastructural facilities. • Tajul Masjid, one of the famous masjids in Asia, is situated in Bhopal. Annual fair of “IZETMA” is held every year in this masjid. A congregation of more than 150,00,000 people takes place during this festival. People from different countries visit Bhopal during this festival.

Indian Lakes, Table 1 (Continued)

Commercial use	For fishing, supply of drinking water, and water sports. An important center for tourism. It is a major source of potable water for the residents of the city, serving around 40% of the residents with nearly 30 million gallons per day. Bada talaab, along with the nearby Chhota Talaab, meaning small lake in Hindi, constitute Bhoj Wetland, which is now a Ramsar site.
Studies undertaken	• Limnological study by Barkatulah University, Bhopal. • Water quality study was undertaken under Bhoj Wetland Project. • Hydrological studies have been conducted by National Institute of Hydrology, Roorkee.
Governing authority	• Madhya Pradesh State Government • Nagar Nigam, Bhopal
General	• Upper Bhopal lake (Bhojtal) was built by Raja Bhoj during his tenure as a king of Malwa (1005–1055). He established the city of Bhopal (also named after him, then as Bhojpal) to secure the eastern frontier of his kingdom. The lake was created by constructing an earthen dam across the Kolans River. An 11-gate dam called the “Bhadbhada dam” was constructed at Bhadbhada in 1965 at the southeast corner of the lake, and now controls the outflow to the River Kaliasote. • Upper Bhopal lake is situated on the west central part of Bhopal city and is surrounded by Van Vihar National Park on the south, human settlements on the east and north, and agriculture fields on the west. It has an area of 31 km², and drains a catchment or watershed of 361 km². The watershed of the Upper lake is mostly rural, with some urbanized areas around its eastern end. The Kolans was formerly a tributary of the Halali River, but with the creation of the lake using an earthen dam and a diversion channel, the upper reach of the Kolans River and Bada Talaab now drains into the Kaliasote River. • Since the construction of the lake in the eleventh century, Bhopal city has grown around it. The people are religiously and culturally attached to the lakes. The lakes meet their needs of water supply and they wash clothes in them (very harmful for the lake ecosystem), cultivate water chestnut in Bhojtal and lotus in Chhota Talaab. The idols of gods and goddesses are also immersed in the lake during religious festivals, though the local administration is advising devotees not to do so. The Takia island in Upper lake has a tomb of the Shah Ali Shah Rahamatullah Alla, which has religious and archaeological significance.

Lakes of Southern India

Lake	Kolleru lake in Andhra Pradesh
Location	Kolleru lake is located in Andhra Pradesh state, India. Kolleru is located between Krishna and Godavari deltas. Nearest city is Vijayawada, which is 65 km by road or rail. Nearest town is Eluru. Kolleru spans into two districts – Krishna and West Godavari.
Location on map	16°39'N 81°13'E to 16.65°N 81.217°E
Surface area	245 km ²
Inflow	The lake serves as a natural flood-balancing reservoir for these two rivers. The lake is fed directly by water from the seasonal Budameru and Tammileru streams, and is connected to the Krishna and Godavari systems by over 68 inflowing drains and channels.
Type of lakes	A large freshwater lake
Ecological status	Grey Herons, Egrets, Painted Storks, and Black-headed Ibises gather in thousands during sunset at Kolleru lake, Andhra Pradesh, India. Rich in flora and fauna, it attracts migratory birds from Northern Asia and Eastern Europe between the months of October and March. During this season, the lake is visited by an estimated 20,00,000 birds. The resident birds include Grey pelicans, Asian Open-billed Storks (<i>Anastomus oscitans</i>), Painted Storks (<i>Mycteria leucocephala</i>), Glossy Ibises, White Ibises, Teals, Pintails, and Shovellers. The migratory birds include Red-Crested Pochards, Blackwinged Stilts, Avocets, Common Red shanks, Wigeons, Gadwalls and Cormorants, Garganys, Herons, Flamingos among others. See the pictures of birds at Lake Kolleru. Kolleru lake contains numerous fertile islets called lankas, and many of the small ones get submerged during floods. The origin of unusual depression which forms the bed of the lake is unknown, but it was possibly the result of an earthquake. Therefore, many ancient villages get submerged in the bed of the lake as a result of floods and earthquake.

Indian Lakes, Table 1 (Continued)

Changes over the last years	Kolleru lake is suffering from the unsatisfied greed of people and selfish interests of mankind who is exploiting the lake's integrity. Thousands of fish tanks were dug up effecting converting the lake into a mere drain. This had a lot of impact in terms of pollution leading to even difficulty in getting drinking water for the local people. This is besides the loss of ecological diversity and intrusion of seawater into the land masses and its fallout in terms of adverse influence of rainfall pattern in this region. This imbalance has an adverse effect on the thousands of acres of crop in the upper reaches of sanctuary in view of stoppages of water flow into the sea because of obstruction by bunds of the fish tanks that appeared illegally. Satellite images taken on February 9, 2001 by the Indian remote sensing satellite found that approximately 42% of the 245 km² lake was occupied by aquaculture, while agriculture had encroached another 8.5%. The area under aquaculture consisted of 1050 fish ponds within the lake and 38 dried-up fish ponds, which together covered an area of 103 km². The agricultural encroachments were mostly rice paddies. Surprisingly no clear water could be found in the satellite image. The rest of the lake is being diminished by water diversions or was infested with weeds like elephant grass and water hyacinth.
Biodiversity	The lake was an important habitat for an estimated 20 million resident and migratory birds, including the Grey or Spot-billed Pelican (<i>Pelecanus philippensis</i>). The lake was notified as a wildlife sanctuary in November 1999 under India's Wildlife Protection Act of 1972, and was designated a wetland of international importance in November 2002 under the international Ramsar Convention. The wildlife sanctuary covers an area of 308 km². Rich in flora and fauna, it attracts migratory birds from northern Asia and Eastern Europe between the months of October and March. During this season, the lake is visited by an estimated 20,00,000 birds. The resident birds include Grey pelicans, Asian Open-billed Storks (<i>Anastomus oscitans</i>), Painted Storks (<i>Mycteria leucocephala</i>), Glossy Ibises, White Ibises, Teals, Pintails, and Shovellers. The migratory birds include Red-Crested Pochards, Blackwinged Stilts, Avocets, Common Red shanks, Wigeons, Gadwalls and Cormorants, Garganys, Herons, Flamingos among others.
Recreation	The sanctuary in the lake has the following watch towers for sighting the birds. Atapaka: 1.5 km from Kaikaluru to see varieties of waterfowl. Murthiraju tank 8 km from Nidamaru East Chodavaram: 53 km from Eluru where Open Bill Storks nest in colonies from July to December. The sanctuary is approachable from all four sides of the lake by road, directly to the following places: Atapaka – 2.5 km from Kaikaluru town, Bhujabalapatnam – 6 km from Kaikaluru town, Murthiraju Tanks – 8 km from Nidamaru, Gudivakalanka – 3 km from Gudivakalanka or 15 km from Eluru. Nearest city is Vijayawada, which is 65 km by road or rail. Nearest town is Eluru.
General	Kolleru lake contains numerous fertile islets called lankas, and many of the small ones get submerged during floods. The origin of unusual depression which forms the bed of the lake is unknown, but it was possibly the result of an earthquake. Therefore, many ancient villages get submerged in the bed of the lake as a result of floods and earthquake. Two copper plates of the early Pallava dynasty have been found in the lake, which trace their history to Langula Narasimha Deva (Langulya Gajapathi Raju) and Ganga Vanshi Orissa king (Oddiya/Oriya raju). According to legend, the Gajapathi fort was located at Kolleti Kota on one of the eastern islands of the lake. The enemy general "muhammadan" (probably a bahamany general) encamped at "Chiguru kota" located on the shores. In some ways, the lake protected the Oriya forces. The enemy finally tries to excavate a channel, the modern-day Upputeru, so that the water of the lake would empty into the sea and the level would fall so that they could attack the Gajapathi Fort. The royal Oriya army general sacrificed his own daughter, named "Perantala Kanama," to propitiate Gods and ensure his success against Muhammadan. Therefore, the channel was called Perantala Kanama. Sri Peddinti Ammavari Temple is one of the oldest and famous temples found in kolleru. The Suryavanshi Gajapatis of Orissa, on the height of their power in the fifteenth century, ruled over a kingdom extending from the Ganges River in the north to the Kaveri in the south under Gajapati Kapilendra Deva. But, by the early sixteenth century, the Gajapatis lost great portions of their southern dominion to Vijayanagar and Golconda. The Gajapatis were a medieval Hindu Suryavamsi dynasty of Kalinga-Utkal Orissa who ruled large parts of Andhra Pradesh, West Bengal, Bihar, and Madhya Pradesh. During the glorious reign of Kapilendra deva, the first Suryavamsi Gajapati emperor, the boundary of the Kalinga empire (Ancient Orissa) stretched from River Ganges in North to Kaveri in South and from Amarkantak in West to Bay of Bengal (Kalinga Sagara) in East.
Lake	Osman Sagar lake, Hyderabad, AP
Location	Osman Sagar, popularly known as Gandipet, is in the Indian city of Hyderabad.
Location on map	17°23'N 78°18'E/17.383°N 78.3°E

Indian Lakes, Table 1 (Continued)

Surface area	The lake is around 46 km ² , and the reservoir is around 29 km ² .
Inflow	Musi River
Outflow	Musi River
Type of lakes	Osman Sagar, popularly known as Gandipet, is an artificial lake
Changes over the last years	This lake had served drinking water for Hyderabad city but due to increase in population it is not sufficient for water supply to Hyderabad city and so now it is used for public recreation.
Recreation	A princely guest house called Sagar Mahal, overlooking the lake, now a heritage building, was built as a summer resort of the last Nizam. It is located on the banks and has the best view of the lake. Andhra Pradesh Tourism Department currently runs the place as a resort. The breeze of the lake is very pleasant and has been popular with the locals since The Nizam's time. It is a popular tourist destination, especially after the rainy season when the reservoir is full, and its parks, resorts, and amusement park are a major attraction.
General	Osman Sagar was created by damming the Musi River in 1920, for providing drinking water source for Hyderabad, and also saving the city from floods, on the lines of which Hyderabad suffered in 1908. It was during the reign of the Last Nizam of Hyderabad, Osman Ali Khan, and hence the name.
Lake	Himayat Sagar, Hyderabad, AP
Location	Himayat is located about 20 km from Hyderabad in Andhra Pradesh, India. It lies parallel to another artificial lake Osman Sagar and it is smaller in size among both.
Location on map	17°18'N 78°21'E TO 17.3°N 78.35°E
Surface area	The storage capacity of the reservoir is about 3.0 TMC.
Inflow	Musi River
Type of lakes	An artificial lake.
Changes over the last years	The Himayat Sagar and Osman Sagar reservoirs provided continuous water supply to the twin cities of Hyderabad and Secunderabad until recently but due to growth in population it was not sufficient for water supply to Hyderabad city. The Engineer at the time of construction is Late Khaja Mohinuddin s/o Mohammed Hussein, Madri.
Commercial use	The grassy area adjoining the lake is an ideal picnic and recreation spot. The road atop the bund is popular for a good road drive.
General	The construction of reservoir on Esi, a tributary of Musi River, was completed in 1927, for providing drinking water source for Hyderabad, and also saving the city from floods, which Hyderabad suffered in 1908. It was built during the reign of the Last Nizam of Hyderabad, Nizam VII, and so it is named after his youngest son Himayat Ali Khan.
Lake	Saroornagar lake, Hyderabad, AP
Location	Saroornagar lake is a lake in Hyderabad, India.
Location on map	17°21'21"N 78°31'38"E TO 17.35584°N 78.52714°E
Surface area	40 ha. The maximum depth is 6 m.
Type of lakes	An artificial lake
Changes over the last years	From the year of its creation in 1626, the lake remained largely clean until 1956 when Hyderabad expanded. It is one of the five major water bodies in Hyderabad. After 1956 when Hyderabad became the state capital of the Andhra Pradesh, the city witnessed unprecedented population growth, industrialization, and agriculture using synthetic fertilizers and insecticides. Inevitably, untreated domestic sewage, solid waste, and industrial effluents entered into the catchment area of this lake. Spread over 40 ha, the lake was restored by the Hyderabad Urban Development Authority in 2003–2004 at a cost of US\$4.44 million. As a part of development, two sewage treatment plants with the capacity to treat 250 million liters of sewage a day were installed. In addition to this, tourism-centric facilities such as a boating facility in the lake, a children's park, and a restaurant have come up. Four years after the installation of the sewage treatment plant, the officials reported 95% of sewage being treated. With the groundwater conditions improved, migratory birds returned to the lake in big numbers. In 2007, 2.0 ha of park area was developed alongside the lake at a cost of US\$333,000. The park featured sculptures, ornamental landscape, boating facility, and an environment education center.
Biodiversity	The lake was restored by the Hyderabad Urban Development Authority in 2003–2004 at a cost of 20 crore (US\$4.44 million). After the restoration of the lake, migratory birds returned to the lake in big numbers a few years later.
Governing authority	After the restoration, the civic agencies have taken necessary steps that the lake does not get polluted because of the annual immersion of Ganesh idols. In addition, steps have taken to curb unauthorized construction near the lake bed. However by 2009, the filtration unit of the sewage treatment plant stopped functioning properly. As a result of this, the lake was getting polluted with domestic waste.

Indian Lakes, Table 1 (Continued)

Lake	Pulicat lake in Andhra Pradesh and Tamil Nadu
Location	45 km north of Chennai.
Climate	Temperate humid climate
Surface area	The lake area is about 72,000 ha (including swamps of 20,000 ha) out of which 46,000 ha is in Andhra Pradesh and 26,000 ha is in Tamil Nadu. The lake is about 60-km long and 5–15 km wide. Average depth of the lake is about 2 m.
Inflow	Fed by two rivers separated from Bay of Bengal by Sri Hari Kota Island. The lake is separated from the sea by a shoal or sediment bar. During monsoon season due to high flood in Pelar river the shoal gets overflowed and lake and sea become one body.
Type of lakes	A natural lake
Ecological status	Pulicat lake has also been given status of bird sanctuary.
Changes over the last years	The marine silt in the islands contains thin layers of gypsum deposited from the seawater during recent time. Sedimentation from catchment area in Andhra Pradesh as well as Tamil Nadu is reducing the lake's capacity.
Commercial use	The lake is used for drinking, fishing, navigation, etc.
Governing authority	Andhra Pradesh Government and Tamil Nadu Government
Lake	Ooty lake, Tamil Nadu
Location	The lake is located in Ooty district in the state of Tamil Nadu, India.
Location on map	11°24'22"N 76°41'18"E to 11.4061°N 76.6882°
Altitude	2,240 m above mean sea level.
Surface area	3.885 km ² , maximum length is 2.5 km, and maximum width is 140 m.
Inflow	The lake was formed by damming the mountain streams flowing down Ooty valley.
Outflow	
Type of lakes	An artificial lake.
Changes over the last years	The lake was initially used for fishing. The lake which breached thrice, completely emptying itself, originally extended up to the present day market. Ferries were used to get across the lake. The lake gradually shrunk in size giving place to the present race course, the bus stand, and the lake park.
Recreation	The Boat house established alongside the lake, which offers boating facilities to tourists, is a major tourist attraction in Ooty.
Governing authority	The Tamil Nadu Tourism Development Corporation on behalf of the Tourism Department took the possession of the lake in the year 1973, for implementation of boating facilities.
General	It was constructed in 1824 by John Sullivan, the first collector of Ooty.
Lake	Veeranam lake, Tamil Nadu
Location	Veeranam lake is located 14 km SSW of Chidambaram in Cuddalore district in the state of Tamil Nadu in South India, 1 km from Sethiyathope.
Location on map	11°20'10"N 79°32'40"E to 11.33611°N 79.54444°E
Surface area	It has a catchment area of 25 km ² .
Inflow	This Veeranam lake gets water from kollidam via Vadavar River.
Type of lakes	It is a reservoir, intermittently filled during monsoon season
Commercial use	The lake located 235 km from Chennai, India, is one of the water reservoirs from where water is planned to be supplied to Chennai.
Studies undertaken	The opening chapter of the much celebrated book <i>Ponniyin Selvan</i> is set on the banks of the Veera Narayanar lake. Kalki gives an elaborate description of the features of the lake and the way multiple rivers flow into the lake. He also makes a reference to the fact, that Ramanujacharya decided on the number of peetas based on the number of openings in the lake.
General	Veeranam lake was created during Chola period in the tenth century, built from A.D. 1011 to 1037 and is a 16 km (10 mile) long dam in northern Tamil Nadu. Ironically, the lake remains dry for a major part of the year.
Lake	Kodaikanal lake, Tamil Nadu
Location	Kodaikanal lake, also known as Kodai lake is located in the Kodaikanal city in Dindigul district in Tamil Nadu, India. A railway line extended from Chennai to Tirunelveli with an intermediate station at Ammaianayakkanur (later renamed Kodai Road) was built in 1875, to provide a gateway to Kodaikanal town and there on to the lake through a foot trek of 18 km from the railhead. The nearest railheads to the lake presently are the Kodai Road Railway Station at 80 km and the Palani Railway Station at 64 km distance, from the town. Madurai (at 121 km) and Coimbatore (at 135 km) airports are the closest to the Lake. Kodai lake is well connected by road with regular bus services operating to Madurai, Palani, Kodaikanal Road, Theni, Dindigul, Thiruchirappalli, Kumili, Erode, Bangalore, and Coimbatore.

Indian Lakes, Table 1 (Continued)

Location on map	10°14'N 77°28'E 10.23°N 77.47°E
Climate	The lake catchment experiences an average annual rainfall of 1,650 mm. The climate is salubrious with summer temperatures of 19.8°C (max) and 11.3°C (min) and winter temperatures of 17.3°C (max) and 8.3°C (min).
Altitude	2,133 m above mean sea level.
Surface area	24 ha with average depth of 3 m and maximum depth of 9 m.
Inflow	An earthen dam was constructed to create the lake in a marshy stretch where three streams flowed.
Outflow	The outflow from the lake forms the waterfall of 180 ft, called the Silver Cascade, 8 km downstream of the lake outlet.
Type of lakes	A freshwater man-made lake. The lake is star-shaped, centrally located in the town of Kodaikanal, and is surrounded by lush green hills of the northwestern Palani hills range, which is the main watershed for the lake.
Ecological status	<i>Flora</i> <i>Strobilanthes kunthiana</i> or Kurinji flower which blooms once in 12 years in the lake's surrounding Palani hills ranges Kurinji (<i>Strobilanthes kunthiana</i>), a unique flowering plant is reported from the catchment area of the lake. It is reported that this flower last bloomed in 2004 and that it blooms once in 12 years. Hill-plantain fruits and plums are popular in the area. <i>Aqua fauna</i> The lake has moderate to dense growth of macrophytes of all types. The littoral zone of the lake is reported to be rich in periphytic biota associated with macrophytes. Diatoms, protozoans, and rotifers which are also associated with macrophytes are found in the lake. Many aquatic insect larvae and adults, molluscs, cladocerans and the fish <i>Danio aequipinnatus</i>, <i>Rasbora daniconius</i> and <i>Gambusia affinis</i> are reported. Rainbow trout and common carp are the main fish found in the lake. The fish yield as per past records was 5.3 kg/ha/year.
Changes over the last years	Human health risk assessment of the physicochemical parameters of the lake water reveals the following: 1. As per microbial analysis, the water is not potable and needs to be processed prior to domestic use. 2. Several ecological factors have influenced the plankton diversity and abundance. 3. Eight aquatic macroinvertebrate taxa have been identified. 4. Tourists and nearby residents are causative factors for lake contamination and water pollution. 5. Encroachment of the banks of the lake by buildings has violated the court order which prohibits constructions within 200 ft from the banks of the lake. 6. The impact on the quality of water is transitory as compared to closed water body. 7. High pollution loads of organic matter from hotels and other commercial establishments around the lake are causing pollution. 8. Study conducted by the Department of Atomic Energy confirmed that Kodaikanal lake has been contaminated by mercury emissions.
Recreation	Over the years a boat club, boathouse, and boat service (with Rowing boats and Pedaling boats and a public ferry) for the public and tourists have become fully functional and is of aesthetic significance for tourism. Boat Pageant and Flower Shows are a regular feature in the summer season which attracts tourists.
Studies undertaken	The Ministry of Environment & Forests, Government of India has initiated a Centrally Sponsored Scheme called the National Lake Conservation Plan (NLCP), since June, 2001, on 70:30 cost sharing basis between the Central Government and the respective State Government, with the objective of restoring and conserving the polluted and degraded lakes in urban and semi urban areas in the country. On the basis of studies carried out, 62 lakes including the Kodaikanal lake in Tamil Nadu have been identified as polluted and degraded requiring conservation. Treatment and eco-restoration works for the Kodaikanal lake were undertaken by the Government of Tamil Nadu with funds provided by the Government of India, under the above stated cost sharing formula, by the National Lake Conservation Plan (NLCP) of the Ministry of Environment and Forests, to abate pollution and, thereby benefit the local and floating population. The project envisaged Bio remediation, Sewage Treatment, Low cost sanitation Facilities, awareness, de- Weeding, Interception and Diversion Works, Fencing, Horse sheds, Data Collection and Dredging, at a total cost of about Rs 10.33 crores (US\$2.6 million).
General	Sir Vere Hentry Levinge, the then Collector of Madurai, was instrumental in creating the lake in 1863, amidst the Kodaikanal town which was developed by the British and early missionaries from USA. The lake is said to be Kodaikanal's most popular geographic landmark and tourist attraction.

Statistics of Indian lakes and studies undertaken on Indian lakes

The statistics of lake water resources in India are scarce. Research conducted after 1947 addressed the ecological, environmental, socioeconomic, and limnological aspects of lakes. Comprehensive statistics of number of lakes have not yet been assessed. A national inventory of lakes entitled "The All-India Wetland Survey" established by the Government of India initiated a study during the 1960s and could only be able to give a broad assessment of wetlands in the country by 1984.

Depending upon the depth of water and uses, the lakes are known by different names in different parts of the country like Jheels, Bheels, Marshes, Talab, and Tank.

Summary of geography, hydrology, ecology, and research undertaken for some of the important lakes in India is given as a table (see Table 1). The positions of the lakes are shown on the map of India (see Figure 1).

Organizations involved in study of lakes of India

Various organizations that are in leading role to study the ecological and limnological aspects of lakes are the following:

Governmental organizations

1. Ministry of Environment and Forests
2. Planning Commission
3. Ministry of Water Resources



Indian Lakes, Figure 1 Map of Indian lakes.

4. Ministry of Agriculture
5. Indian Board for Wildlife
6. Forest Research Institute
7. Ganga Water Authority
8. Institute of Wetland Management and Ecological Design
9. Environmental Monitoring Organizations
10. National Eco-Development Board
11. National Institute of Oceanography in Goa

Nongovernmental organizations

1. Bombay, Natural History Society
2. WWF – India
3. UNDP/UNESCO
4. French Institute, (Pondicherry)
5. Ecological Society, (Pune)
6. Wildlife Preservation Society of India (Dheradun)
7. Tourism and Wildlife Society of India (Jaipur)
8. Assam Valley Wildlife Society (Guwahati)

Academic institutions

1. Andhra University, Visakapatnam
2. Annamalai University, Annamalai (Tamil Nadu)
3. Barkatullah University, Bhopal
4. D.N.R. College, Bhimavaran
5. Guwahati University, Assam
6. Jawaharlal Nehru University, New Delhi
7. University of Jodhpur, Jodhpur
8. University of Kashmir, Srinagar
9. Osmania University, Hyderabad
10. University of Rajasthan, Udaipur
11. Indian Institute of Technology, Roorkee
12. Sourashtra University, Rajkot, Gujarat
13. Pondicherry University, Pondicherry

National Institute of Hydrology is the only institute engaged in hydrological studies of lakes through its headquarters at Roorkee and also through its Regional Centers at Jammu, Patna, Guwahati, Belgaum, Kakinada, and Sagar.

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Cross-references

Bengal Basin, Sediment Sink
 Chilika Lake
 Eutrophication in Fresh Waters: An International Review
 Restoration of Urban Lakes in the NE Musi Basin, Hyderabad, India
 Udaipur, Lakes
 Water Balance of Lakes
 Water Quality in Lakes and Reservoirs

INITIAL MIXING OF POLLUTANTS

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Synonyms

Near-field mixing of pollutants

Definition

The initial mixing of pollutants in a lake or a reservoir refers to the processes which mix discharged polluted water with receiving (ambient) water in a zone near the discharge point, where the initial properties of the discharge are important for the mixing processes. Initial properties of the discharge include fluxes of volume, momentum, and buoyancy, as well as geometric characteristics of the discharge. Beyond the zone of initial mixing (i.e. far field), only the properties of the ambient (e.g., *hydrodynamics*, *stratification*, and geometry) will determine the mixing.

Lakes and reservoirs are often used as receiving waters for different types of pollution discharge, for example treated waste water, industrial process water, and cooling water from power plants (Jirka et al., 1996). The discharge of the polluted water typically occurs through a nozzle, or a system of nozzles, as a buoyant jet with a certain initial volume (Q_o), kinematic momentum (M_o), and kinematic buoyancy (B_o) flux. Dimensional analysis is often employed to characterize the buoyant jet and its mixing with the ambient. In such analysis, based on Q_o , M_o , and B_o , two length scales emerge (Fischer et al., 1979), namely $l_Q = Q_o/M_o^{1/2}$ and $l_M = M_o^{3/4}/B_o^{1/2}$. The length scale l_Q quantifies the distance over which Q_o constitutes a significant portion of the local jet volume flux (i.e., the entrained ambient water and Q_o is of the same order). Thus, for distances from the nozzle (s) much larger than l_Q , Q_o will not be of significance. The length scale l_M represents the distance over which the buoyancy generates a momentum flux similar to M_o . For $s \gg l_M$ the effect of M_o is negligible and the buoyant jet becomes a plume. Thus, the extent of the initial mixing zone is often defined based on l_M , since $s \gg l_M$ implies no influence from the initial conditions. Relationships for different jet quantities in the near field, such as velocity, volume flux, and dilution rate may be developed in terms of l_Q and l_M .

If a jet discharge is affected by a boundary, the length of the initial mixing zone could be determined by the location of this boundary. The lake water surface and bottom represent such boundaries (for positively and negatively buoyant jets, respectively), but *stratification* may also act as a boundary.

The highest pollutant concentrations are found in the zone of initial mixing, and the impact on *water quality* is expected to be the largest in this zone. However, since the mixing to a large degree is a function of the initial conditions, it is feasible to reduce the impact through a proper design of the discharge arrangements. In general, the dilution rate is considerably larger in the near field compared to the far field.

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Cross-references

Basin-Scale Internal Waves
 Circulation Processes in Lakes
 Geneva Lake
 Hydrodynamics and Circulation of Fjords
 Internal Seiches
 Mixing in Lakes
 Riverine Thermal Bar
 Stratification in Lakes
 Surface Seiches
 Thermal Regime of Lakes

INTERNAL SEICHES

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Definition

An internal seiche is a standing wave produced in the interior of a lake at the thermocline level.

When wind blows over a lake, a storm surge is produced that causes the thermocline to tilt in the opposite direction (Figure 1). Once the wind ceases, the thermocline, which forms a sharp interface due to the strong density gradient, begins to oscillate around the nodal point in the center of the lake. This is the point that experiences no vertical motion during a seiche cycle (Figure 1). Maximum amplitudes are observed at the antinodes at the ends of the lake basin. This phenomenon was first interpreted as an internal seiche by Watson (1904).

To determine internal seiche periods, the effect of stratification must be considered. It is assumed that an observed stratification profile can be approximated by a two-layer profile in which the density of each layer is constant. The Merian equation valid for “surface seiche” periods must be modified so as to take into account the difference between the water density of the epilimnion (ρ_1) above and the hypolimnion (ρ_2) below the thermocline. Furthermore, the mean thickness of the epilimnion, h_1 , and the hypolimnion, h_2 (Figure 1), enters into the calculation. The restoring force for this oscillation is proportional to the product of gravity and the density difference between the two layers (the relative buoyancy).

The following equation for internal seiche periods can be obtained:

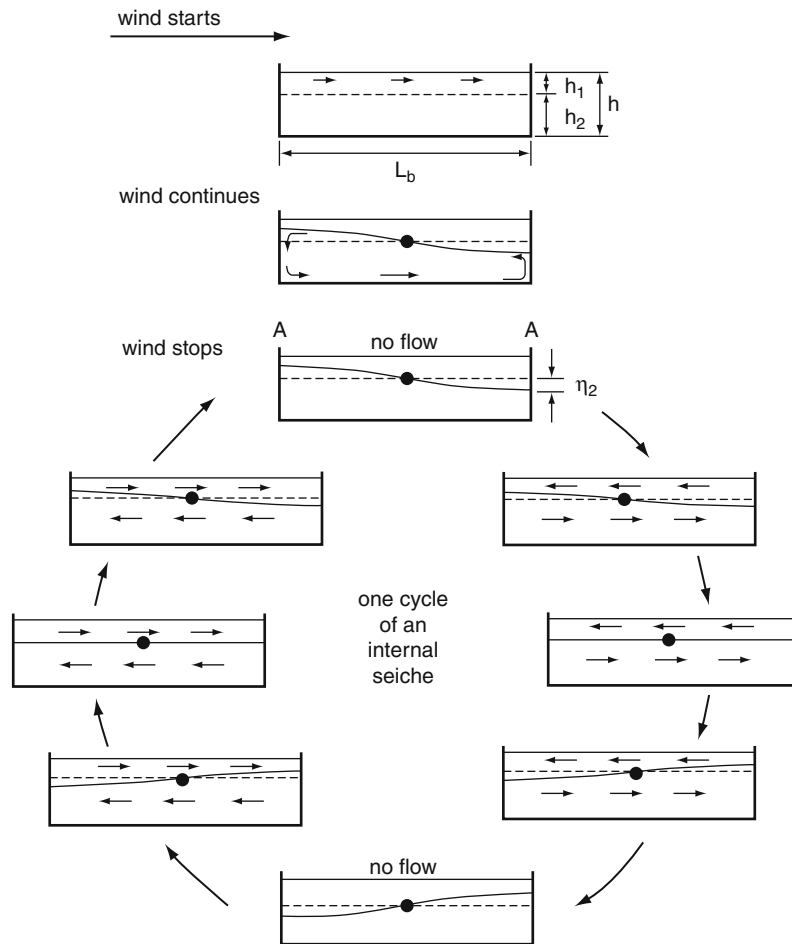
$$P_n = \frac{2L_b}{n} \sqrt{\frac{(h_1 + h_2)}{h_1 h_2 g}} \quad (1)$$

This is the modified Merian equation for internal seiches with n being the wave mode. Here, $g = g(\rho_2 - \rho_1)/\rho_2$ is the reduced gravity. Although this equation was derived for rectangular basins, it was also found to give good estimates for real lakes. Uninodal internal seiches of the mode $n = 1$ have been found to be a widespread, dominant resonant response of stratified lakes to wind stress. Periods of internal seiches are much longer than those of “surface seiches” and are typically in the range of hours (about 76 h for $n = 1$ in “Lake Geneva”).

Using the two-layer assumption, the ratios of the surface inclinations η_1/η_2 and the horizontal velocities v_1/v_2 in the epilimnion and the hypolimnion, respectively, can be approximated by

$$\eta_1/\eta_2 \approx -g'h_2/gh \text{ and } v_2/v_1 \approx -h_1/h_2. \quad (2)$$

Due to the small density difference between the epilimnion and the hypolimnion, seiche amplitudes, η_2 ,



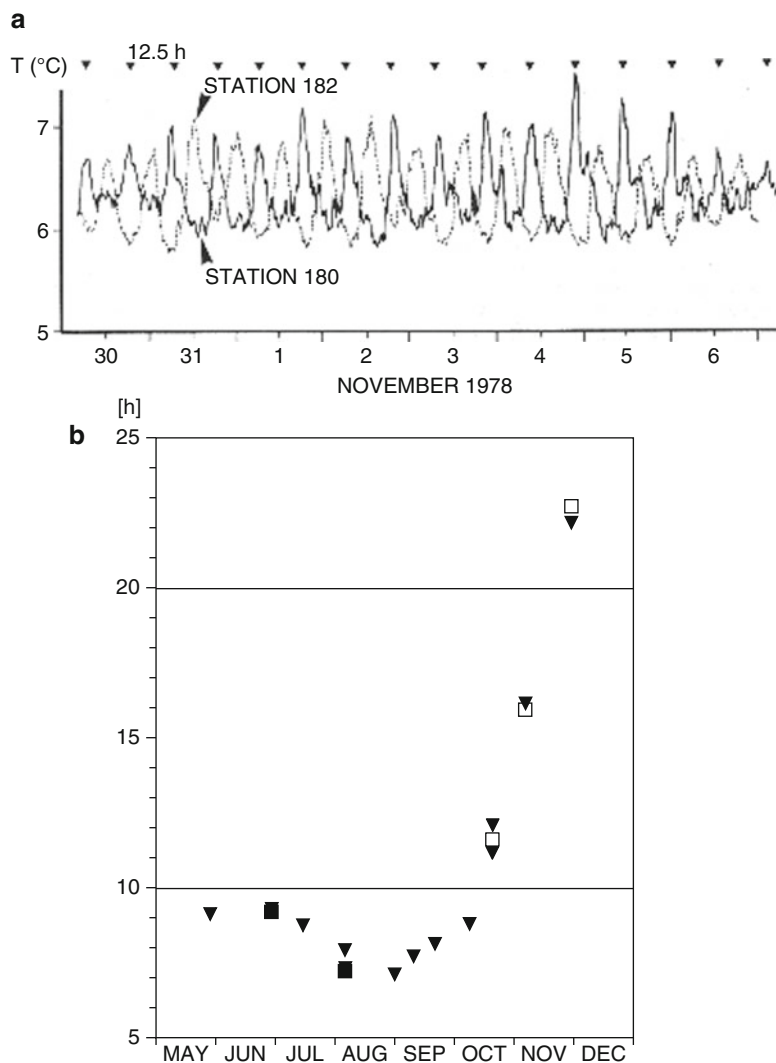
Internal seiches, Figure 1 Definition sketch for a two-layer approximation of a uninodal internal seiche in a stratified rectangular lake basin. *Black dot*: nodal point, *A*: antinodes, *dashed line*: still water reference level of the thermocline, *arrows*: mean orientation of water mass movement.

are typically several meters high (2). Consequently, the currents in the two layers are of the order of several cm s^{-1} , with epilimnion currents being stronger than those in the hypolimnion (2). These currents are comparable to other water movements in lakes. Horizontal currents in internal seiches are strong near the surface and bottom and minimal at mid-depth. The rate of decay is determined by boundary friction and is higher for shallow basins or basins with irregular shape. A numerical procedure to determine internal wave periods and current estimates in irregular shaped basins has been proposed by Lemmin and Mortimer (1986).

Internal seiches are found in lakes throughout the stratified season and can be regular and persistent for long time periods (Figure 2a). Their period is well approximated by the modified Merian equation (1). The effect of

changes in the density difference between the two layers and to some extent also in layer thickness over the stratified season is reflected in the strong seasonal variation of the internal wave period (Figure 2b). Higher mode internal seiches, most often with smaller amplitudes than the first mode, have been observed in lakes. In Lake Baldegg, seiches up to $n = 5$ were simultaneously detected.

The two-layer approximation for the temperature profile is a strong simplification, since the temperature in lakes varies continuously with depth. If a three-layer approximation is made, second vertical mode internal seiche periods can be estimated which are longer than the first mode periods. In Lake Baldegg, the fundamental second vertical mode period was 28.9 h compared to 9 h for the first vertical mode. Second vertical mode seiches result in a periodic change of thermocline thickness.



Internal seiches, Figure 2 Internal seiches in Lake Baldegg (Switzerland; from Lemmin, 1987). (a) Temperature recordings at 15-min intervals at 12.5-m depth at stations 180 and 182 at opposite ends of the lake basin in November 1978. Triangles indicate the period calculated by the modified Merian formula. (b) Seasonal variation of the period of the first mode internal seiche oscillation in 1980.

In large lakes, the influence of Coriolis force transforms a standing internal seiche into a Kelvin wave with the standing seiche pattern shown in [Figure 1](#) rotating counterclockwise (in the northern hemisphere) around the lake basin. It has the same period as a standing internal seiche.

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Cross-references

[Basin-Scale Internal Waves](#)
[Circulation Processes in Lakes](#)
[Geneva Lake](#)
[Mixing in Lakes](#)
[Riverine Thermal Bar](#)
[Stratification in Lakes](#)
[Surface Seiches](#)
[Thermal Regime of Lakes](#)

JAPANESE LAKES

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Synonyms

Inland water bodies of Japan; Reservoirs of Japan

Definition

Lake. A lake is an inland and permanent body of water containing a considerable amount of fresh or saline water.

Reservoir. A reservoir is an artificial lake.

Eutrophication. A heavy load of nutrients in a body of water.

Algal bloom. A great increase of phytoplankton in a body of water as a result of eutrophication.

Natural lakes and their formation

Many Japanese lakes are geologically isolated natural waters, not connected to an ocean or river. Some of them were formed by intrusion of seawater into the offshore land after the last glacial age. Shallow inner bays were formed; sediments transported by river inflows were then accumulated in the bays and isolated the water from the sea. Therefore, many lagoons, such as Lake Kasumigaura, Lake Saroma, Lake Shinji, and Lake Ogawara, are located along the coastal line. Among the five lakes around Mt. Fuji (Lake Motosu, Lake Shojin, Lake Sai, Lake Kawaguchi, and Lake Yamanaka), Lakes Onuma, Chuzenji, and Inbanuma are, in fact, rivers that were dammed with accumulated debris from the surrounding volcanoes. The accumulation of decaying plant materials also interrupted river flows and created inundated areas.

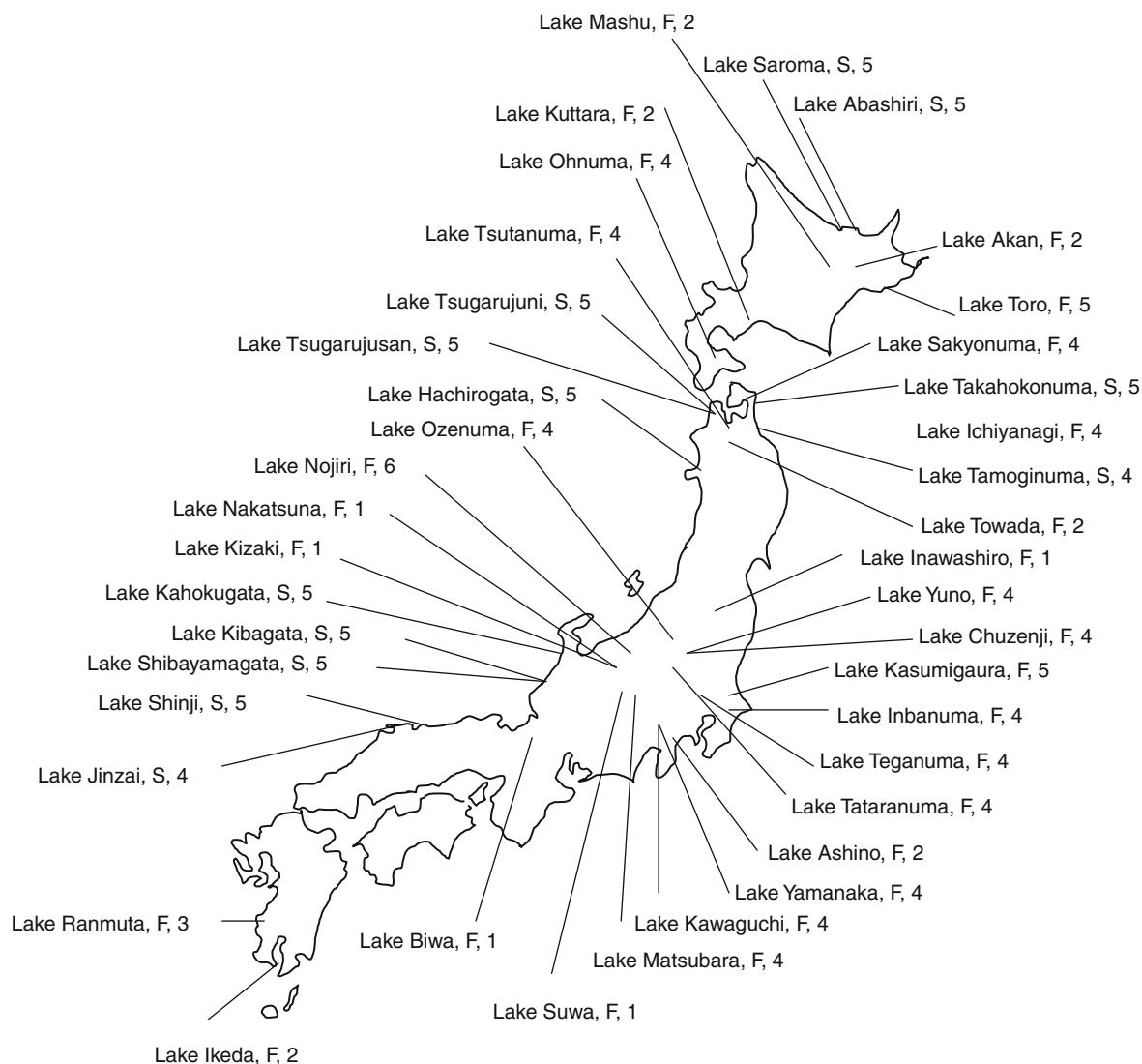
Lakes created by this mechanism - Lake Ozenuma, for instance - are relatively small.

Since Japan is situated in a volcanic zone, many lakes have been created due to its geological features. Diastrophism is a mechanism by which many lakes, such as Lakes Biwa, Suwa, and Kizaki, were formed. The development of these lakes is associated with seismic faults. Lakes formed in volcanic craters or calderas are called crater lakes. Lakes Tazawa, Ashino, Towada, Inawashio, Akan, and Kuttara belong to this group and are generally deep with relatively small catchment areas. Lakes Mikazukinuma and Nougaike in Kiso and Lake Barato on Hokkaido were created due to severe river erosion. [Figure 1](#) shows the major Japanese lakes and their origins.

Reservoirs

Since 8 CE, more than 200,000 irrigation ponds have been constructed in Japan. Seventy percent of these ponds were constructed in western Japan, as in the Kinki district (near Osaka) and around the Seto Inland Sea, due to the scant annual precipitation of this area. The largest pond, Mannoike, with an area of 1.4 km², was constructed in 9 CE. These irrigation ponds are of two major types: dammed rivers and swamps surrounded by embankments. The latter group is usually flat and shallow and has a special ecosystem. From ancient times, various types of management practices, such as drying up (Maezono and Miyashita, 2004) or harvesting of overgrown plants, have been conducted by local people to maintain these bodies of water. Therefore, the ponds provide suitable habitats to various kinds of aquatic flora and fauna. They have high biodiversity and can harbor many endangered species (Kunii, 1991; Jiang and Kadono, 2001).

Since the 1950s, many dams have been constructed on mountainous rivers to control floods; the reservoirs formed, thereby, have been used to generate hydroelectric



Japanese Lakes, Figure 1 Locations of major Japanese lakes. F and S represent lakes with fresh and saline water, respectively. Each lake's origin is shown by the numbers: 1 – fault lake; 2 – caldera lake; 3 – volcanic lake; 4 – dammed lake; 5 – lagoon; and 6 – other.

power and to supply water for various utilities. Since the reservoirs were created along the valleys, they are long, narrow, and deep, and thus, they have relatively small storage capacity and short retention period of water regardless of the height of the dam. In total, there are approximately 3,000 dams, of which 14% are used for hydroelectric power generation, 36% for irrigation, 19% for flood control, and 12% for more than one purpose. The largest reservoir in Japan is the Tokuyama reservoir, with a storage capacity of 660 million cubic meter, although the height of the dam is 161 m.

History of Japanese natural lakes

There were many shallow lagoons in the flat plain and coastal zone before 17 CE, when many of them were reclaimed and converted to rice fields. Since the Meiji

era 150 years ago, due to increasing urban population, the surrounding area of lakes has become densely inhabited. As a result, lakeshores have been further reclaimed to develop residential areas. Since 1945, land gained from reclamation area has totaled approximately 347 km² (Ministry of Environment, 1996), which corresponds to ~13% of the total lake area.

Dynamics of lakes and oxygen condition

Since they are located in a temperate zone, most of the freshwater lakes in Japan are holomictic (Akitomo et al., 2009a, b). Their hypolimnion is oxygenated at least once a year, inhibiting the formation of an extreme anoxic zone at the bottom; therefore, they are relatively rich in oxygen. For example, in Lake Biwa, the average dissolved oxygen concentration of the lower layer was 7.1 mgL⁻¹

between 1991 and 2009 at the Imadzu Oki Chuo station (LBERI, 2011). Brackish water lakes, on the other hand, have strong saline stratification, which inhibits convective mixing except for shallow lakes, and the lower layers of polluted lakes, such as Lake Abashiri (Mikami et al., 2002), Lake Obuchi (Ueda et al., 2005), and Lake Shinji, are highly anoxic, which causes mortality even to benthic organisms.

Since the reservoirs are deep and narrow, the wind disturbance therein is weaker. Therefore, once the catchment is developed, the hypolimnion easily becomes anoxic with an increasing inflow of pollution. In western Japan or near large cities with relatively dense population and dairy farming on the gradual mountain slopes, inflows are often highly eutrophic. Hypolimnetic anoxic zones have been found to develop in many reservoirs between September and October.

Water quality

Since the 1960s, many Japanese lakes, particularly those in suburbs or large cities, have become polluted due to urbanization and industrialization. Between 1974 and 2001, the worst water quality in terms of chemical oxygen demand (COD) was observed in Lake Teganuma (Shinohara and Isobe, 2010). Cyanobacterial blooms have appeared in many Japanese lakes in recent years due to eutrophication. For example, in Lake Biwa, cyanobacterial blooms have been appearing particularly in summer since 1983. Since then, various restoration techniques have been tried to address the issue. Flushing with river water (e.g., Lake Teganuma (Asaeda et al., 2005) and Lake Barato (Shinohara et al., 2008)), bypassing of treated sewage water (e.g., Lake Suwa) or polluted inflows (e.g., Urayama Dam), and drying the bottom sediment (e.g., Watarase Reservoir (Asaeda and Rashid 2010)) were successfully implemented. Destratification with bubblers is another commonly used technique to reduce cyanobacterial biomass (Imteaz and Asaeda, 2000). Installation of lateral curtains to isolate eutrophic inflows from the epilimnion was also effective in reducing *Microcystis* and dinoflagellates in some reservoirs (Asaeda et al., 1996, 2001).

The littoral zones of many Japanese lakes were covered with aquatic plants until the 1960s (Kasaki, 1964), before which the plants had been used to prepare organic fertilizer for riparian agriculture. However, since the 1970s, these submerged plants have disappeared from almost all large lakes, except for Lake Biwa. Several causes have been associated with the disappearance of these submerged plants (Watanabe et al., 2005). Eutrophication of the lakes and reduction in transparency is one of the important reasons. These lakes were oligotrophic, and their water was transparent until the 1970s when urbanization and industrialization started around these lakes. Since then, pollutants from the urbanized catchments have been inflowing into the lakes, and aquatic plant population decreased to a great extent. In Lake Towada, for instance, the deeper edge of the charophyte zone decreased from 13 m in 1955 to 7.5 m in 2002. In 1960s, grass carp was

introduced in many lakes, such as Matsubara, Kizaki, Nojiri, and Ikeda. Being voracious herbivores, they ate all the submerged grasses. Although the carps cannot propagate, in lake, they keep grazing on macrophytes until their death.

Since organic pollutants from the catchment areas accumulate at the bottom, sediment has been dredged from many lakes to remove the pollutants from lake. Consequently, bottom irregularities were formed that have led to an anoxic zone on the bottom. Due to dredging, seed banks of aquatic macrophytes were removed, and water depth reduced near the shoreline. The exploitation of the shoreline due to embankment construction around the lakes was prominent in many large lakes during flooding. As the embankment was constructed near or even inside the water to gain more land, it separated land and water and exploited the shoreline. The continuity of shoreline vegetation communities was lost. These processes also affected submerged vegetation communities. The reduction in vegetation by this mechanism is evident at Lake Kasumigaura. The disappearance of submerged aquatic macrophytes also coincided with the usage of chemical herbicides in agricultural fields located in catchment areas.

Exotic species

Ecosystems of many Japanese lakes are suffering from introduced exotic species. Exotic predatory fish, especially *Micropterus salmoides* and *Lepomis macrochirus* (Centrarchidae), are prominent in many Japanese lakes. They were introduced into Japan, to be used for human consumption, in 1925 and 1960, respectively. Starting in the 1970s, they were introduced into many lakes to promote sport fishing (Azuma, 1992), which eliminated many Japanese native fishes. This incidence posed a serious threat to the lake's ecosystem and inland fisheries (Takamura, 2007).

Lake Biwa

Lake Biwa is the largest lake in Japan and is a freshwater lake. Its total surface area is 670.3 km², and it is 27.5 km³ in volume. The deepest point is 103.6 m. Lake Biwa is an ancient lake, originated through diastrophism approximately 4–6 Ma ago, and is one of the oldest lakes in the world, following Lake Baikal and Lake Tanganyika. It is a mesotrophic lake with approximately 6.0 m of Secchi depth. Until 1952, Lake Biwa had approximately 40 shallow lagoons along its shoreline, which provided habitats for various species (Mori, 1980). The lake had extremely high biodiversity, with more than 1,000 plant species, including more than 50 native plants, such as *Silurus biwaensis*, *Silurus lithophilis* (Siluridae), *Gnathopogon caeruleus*, *Sarcocheilichthys variegatus microoculus*, *Sarcocheilichthys biwaensis* (Cyprinidae), *Vallisneria asiatica* var. *biwaensis* (Hydrocharitaceae), and *Potamogeton biwaensis* (Potamogetonaceae). Since 1952, the water level has been regulated down for flood protection, and most of the lagoons were reclaimed.

Since then, the landscape of the lake has changed remarkably, and the population of the flora and fauna inhabiting the lake had been diminishing until a recent renovation. Submerged plant coverage has increased substantially since the end of the 1990s, especially at the southern basin, which is approximately 4 m deep (Haga et al., 2006). Approximately 43% of the total basin was covered in 2000. The colonization is supposed to be the regime shift of the water transparency. In 1994, the water level of the lake was drawn down by 1.23 m, which is believed to trigger the germination of submerged species (Hamabata and Kobayashi, 2002).

Lake Kasumigaura

Lake Kasumigaura, a shallow lake, is the second largest in Japan (220.0 km² in total area). Though the lake is separated into several waters now, it originated as part of a large lagoon. Its water was brackish until 1963 when a gate was constructed to preclude the brackish water's intrusion into irrigation and domestic use. Due to the inflows of sewage and refractory dissolved organic matter from the catchment (Imai et al., 2001), the lake was eutrophicated and has been suffering from cyanobacterial blooming. The blooming was caused by *Microcystis aeruginosa* until the 1980s when the dominance shifted to *Oscillatoria*. The switch of the cyanobacterial species is thought to be the increase in N/P ratio in water from ~8 to 16. The shoreline was covered with emergent plants (Sakurai, 1990; Nishihiro et al., 2006) until the construction of the surrounding embankment, which reduced their population to a great extent. Fisheries of Japanese smelt (*Hypomesus nipponensis* (Osmeridae)), icefish (*Salangichthys microdon* (Salangidae)), carp, and Japanese eel have been popular in the lake. The introduction of *Ictalurus punctatus* (Ictaluridae), however, has been causing many problems in recent years.

Effect of climate change

The effects of global warming are evident in some Japanese lakes. In Lake Biwa, although all the layers are mixing, the mixing time has been delayed. The layer mixing usually occurs in January; however, it was delayed until the beginning of March in 2007 (Yoshimizu et al., 2010). In the Sagami and Tsukui reservoirs, 40 km west of Tokyo, the destratification system to protect algal blooming, which had been working very well for a decade, has not worked for the last few years. In addition to the increased warming of the epilimnetic water, the cold water inflow due to snow-melt is being reduced (Asaeda and Rashid 2010). Although more investigation is required, climate change and warming seem to be affecting Japanese lake conditions.

Summary

Japanese lakes and reservoirs are an integral part of inland aquatic ecosystems. They are rich in biodiversity and provide many important functions in land–water interfaces. Due to anthropogenic reasons, especially urbanization and industrialization, the water quality of the lakes and

reservoirs has deteriorated noticeably in last few decades. As a result, a number of aquatic flora and fauna have disappeared, and many of them are on their way to extinction. Though many mitigation approaches have been adopted and the situation has improved to some extent in recent years, the issue has come forward again due to global climate change. Therefore, more research should be allocated to keeping Japanese lakes and reservoirs functional.

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Cross-references

[Asia, Lakes Review](#)
[Thermal Regime of Lakes](#)
[Water Balance of Lakes](#)

K

KATSE DAM: LESOTHA HIGHLANDS WATER PROJECT

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Description

The Katse Dam is located in Lesotho in the Central Maluti Mountains in the Malibamatso River ([Figure 1](#)). The dam is of the concrete arch type with a height of 155 m. The

primary purpose of the dam is to supply water to the Republic of South Africa (RSA) and to generate hydropower (110 MW). The reservoir has a total storage of 1950 hm³ ([Table 1](#)). The dam was commissioned in 1998 as part of the Lesotho – RSA Highlands Water Project ([Figure 2](#)).

The water is delivered by a series of tunnels by way of the Rivers Caledon, Ash, and Wilge and eventually into the Vaal River to RSA.

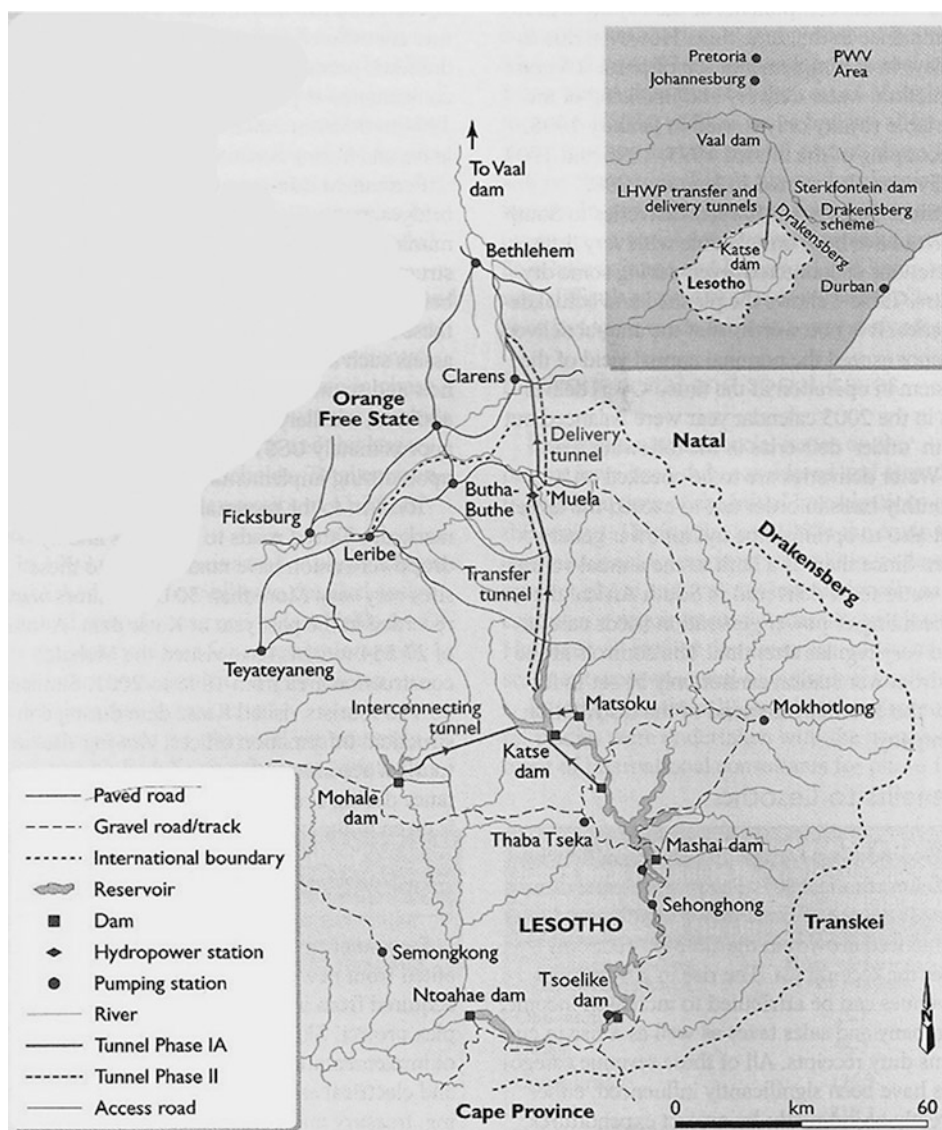
The Mohale dam (height 153) and the Muela dam were also built under the Lesotho – RSA Highlands Water Agreement and commissioned in 2004.



Katse Dam: Lesotha Highlands Water Project, Figure 1 Katse dam (Jackie van Bosch RSA).

Katse Dam: Lesotha Highlands Water Project, Table 1 Main features of the highlands water project

Main reservoirs	Katse	Matsoku	Mohale	Mashai ^a	Muela
Catchment area (km ²)	1,866		945	7,978	
Mean annual runoff (hm ³)	622		315	1,615	
Total storage (hm ³)	1,950		958	3,430	5.9
Active storage (hm ³)	1,519		720	2,430	3.9 MW
Supply level (masl)	2,035	2063	2,075	1,887	1,775
Operating level (masl)	1,989		2005	1,835	1,760
Type of dam	Arch	Diversion water	Embankment	Embankment	Arch
Height (m)	180		140	170	55
Crest length	710		564	680	180
Volume of dam (hm ³)	2.2		8.5	14.4	0.85
Hydropower (MW)	110				72

^aFuture development**Katse Dam: Lesotha Highlands Water Project, Figure 2** Lesotho location of dams (After Tromp 2006).

The system harnesses the water resources of the highlands of Lesotho to the mutual advantage of South Africa and Lesotho, the key benefit to the latter being the royalty income for the sale of water.

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[Hydropower](#)
[Large Dams and Environment](#)
[Large Dams, Statistics and Critical Review](#)

KINGAIRLOCH HYDROELECTRIC SCHEME

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Introduction

People have been harnessing water to perform work for thousands of years. The Greeks and Chinese used water wheels for grinding wheat into flour and for powering wood and textile water mills 2,000 years ago.

However, the technology of using water to create electricity was first established successfully when in the mid 1770s the French engineer Bernard Forest de Belidor developed the vertical-axis turbine.

Worldwide today the installed capacity of hydroelectric power stations is of the order of 750 GW (where $G = 10^9$) supplying some 3,000 TWh (where $T = 10^{12}$).

Hydroelectric power plants may be as small as 100 KW of power to the world's largest, the Three Gorges Dam in China with a capacity of 22,500 MW.

In some countries (Norway, Switzerland, Canada, Brazil, New Zealand, Venezuela, Paraguay, and Austria), hydroelectric power is the main source of electricity.

Hydroelectric projects can sometimes create problems for the environment such as reducing fish population by preventing access to spawning grounds upstream. And indeed, a few dams have been withdrawn because of this and other environmental problems. Nevertheless, although in many cases most of the hydroelectric sites have already been exploited, installations, especially small schemes under 10 MW, continue to be built in many areas of the world. The major advantage of these small projects is their geographic isolation, the elimination of the cost of fuel, their long economic lives, and their production of the least amount of greenhouse gases of any energy source.

One such project recently completed (2010) is the Kingairloch scheme in the UK (see photograph showing dam under construction for [Figure 1](#)).

Kingairloch

Kingairloch hydro scheme is situated in an isolated area of the Western Highlands in Morven; the scheme is one of



Kingairloch Hydroelectric Scheme, Figure 1 Dam under construction.

renewable investment and comprises a power station with a horizontal Francis turbine, a 6-m-high concrete gravity dam, two main intakes, two high pressure GRP pipelines, and three buried pipe aqueducts.

The development of the scheme concept was based on using the existing reservoir at Loch Uisge and raising it by 3 m. The new reservoir capacity is of the order of 700,000 m³. This gives storage of 1.4% of annual runoff and allows 3 days generation at full load with no inflow. The reservoir gives considerable benefits in greater flexibility, the ability to maintain compensation flows through dry spells and easier control and greater efficiency of the turbine which runs at a fixed load of 3.5 MW.

Power generation is a function of flow and head, and in this case, the head is 143 m and the discharge is 3.23 m³/s.

The dam is 110 m in length made up of 30-m and 50-m abutments, a 20-m overflow spillway and a 10-m inlet structure. Abutments are of mass concrete while the central section is reinforced. The dam also includes fish passes and provision for releasing water if necessary.

Acknowledgment

Acknowledgment is made to Scottish and Southern Energy (SSE) for Figure 1.

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Hydropower
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KIS-BALATON AND ITS EFFECT ON LAKE BALATON WATER QUALITY

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Description of Lake Balaton

Lake Balaton is the largest calcareous shallow lake in Central Europe and is situated in the western part of Hungary, in Transdanubia (46°62'–47°04'N, 17°15'–18°10' E). The lake is primarily used for recreational purposes (Figure 1). The surface area is 596 km², but the mean depth is only 3.2 m and the mean water residence time is 5 years (Table 1). The only outflow is at the eastern end of the lake where a control gate was built in 1863. River Zala enters the westernmost basin and drains about half of the catchments (5,775 km²). There are 51 minor inflows, 20 of which are permanent.



Kis-Balaton and Its Effect on Lake Balaton Water Quality, Figure 1 Lake Balaton scenery during a calm sunny day. (Photo by Balaton Club Co., <http://www.balatonclub.hu>).

Kis-Balaton and Its Effect on Lake Balaton Water Quality, Table 1 Hydrological, chemical and biological characteristics of Lake Balaton

Water surface	59,000 ha
Length	77 km
Width	8–16 km
Maximum depth	11.2 m
Mean depth	3.2 m
Water residence time	3–8 years
Mean annual water temperature	12.2°C
pH	8.4–8.7
Conductivity	660 µS cm ⁻¹
Maximum summer chlorophyll-a values	
Eastern basin	17.6 µg L ⁻¹
Middle basin	47.1
Western basin	60.6

The water of the lake is frequently turbid because of sediment resuspension and calcite precipitation (Istvánovics et al., 2004).

During the past 30–35 years, Lake Balaton has been heavily impacted by human activities. High-point and non-point sources of nutrient loading have led to heavy eutrophication (Herodek, 1986). Cyanobacterial blooms occurred during summer, and massive repeated fish kills were observed (Bíró, 1997). Eutrophication and habitat perturbation (e.g., decreased water level fluctuations, climate change leading to increased temperature, decreasing drainage area) led to a drastic decrease in the number of fish species, stock recruitment success, and increasing water temperature in Lake Balaton (Specziár et al., 1997; Bíró, 2000). To combat eutrophication, the Hungarian government has initiated several action plans aimed to reduce the external nutrient loading and nutrient retention. To accelerate recovery of Lake Balaton, chemical and biological restoration methods have been applied between 1985 and 2002.

In order to manage nutrient loads and enhance improvement in water quality of Lake Balaton, Kis-Balaton Water

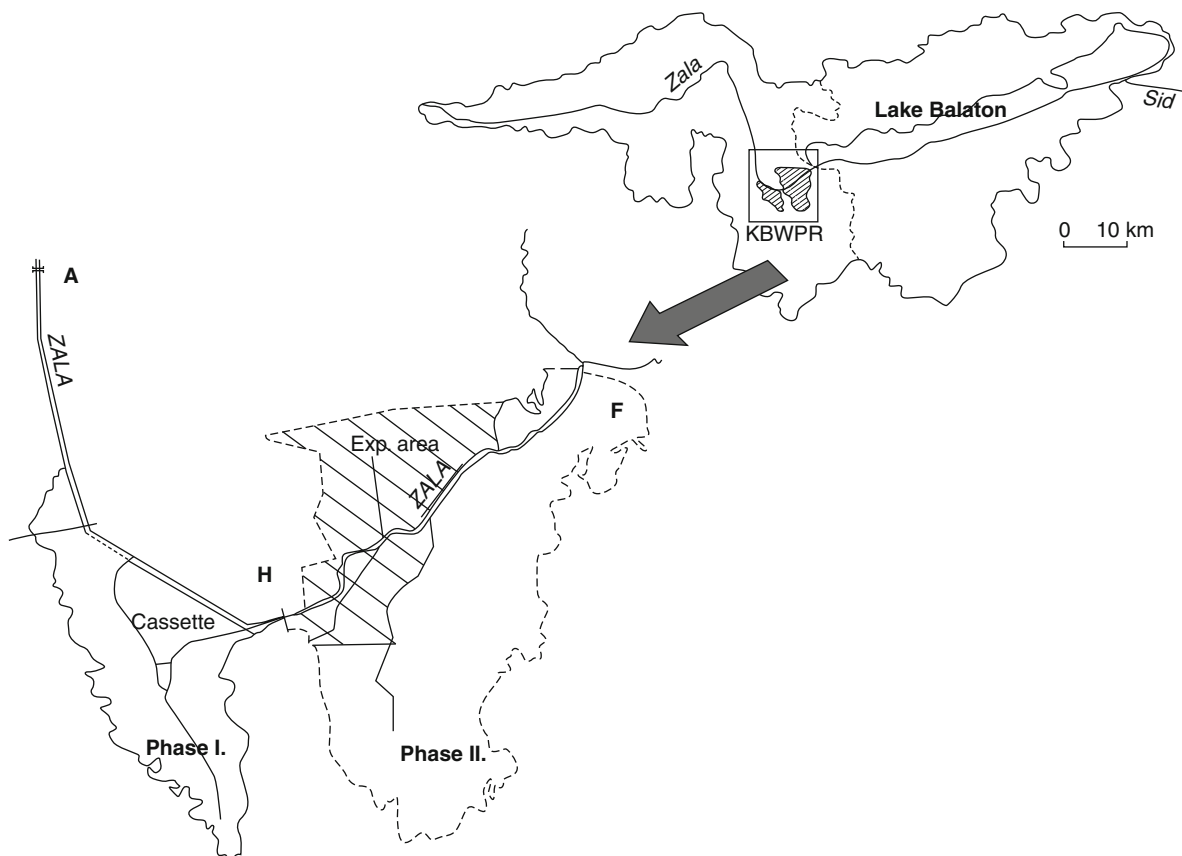
Protection Reservoir (KBWPR) was constructed in the lower Zala River Valley, the main inflow to the lake (Figures 2, 3). In this entry, we describe the actions taken to reduce the external and internal loadings and the response of the ecosystem to the reduction.

Description of the Kis-Balaton water protection reservoir

Construction of the Kis-Balaton Water Protection Reservoir (or System) (KBWPR) ($46^{\circ}78'N$, $17^{\circ}27'E$) (Figure 2) was planned in two phases (Figure 3). The first



Kis-Balaton and Its Effect on Lake Balaton Water Quality, Figure 2 The two phases of Kis-Balaton Water Protection Reservoir: Phase I (left) during early summer and Phase II (right) during fall. (Photo by Transdanubian Water Authority, Kis-Balaton Laboratory at <http://www.kisbalaton.hu/kepek.html>).



Kis-Balaton and Its Effect on Lake Balaton Water Quality, Figure 3 Lake Balaton and its watershed area. The Kis-Balaton Water Protection Reservoir (KBWPR) is enlarged. Experimental area (16 km^2) of Phase II has been operating since 1992. The rest of Phase II is planned to be operating by 2012 (A, input to the KBWPR I; H, output of the KBWPR II; F, input to Lake Balaton).

phase (Phase I), called Hídvégi Pond, started to function in 1985. It is a hypertrophic pond, with a surface area of 18 km², a mean depth of 1.1 m, and a mean water retention time of 30 days. The pond, called “Cassette,” was implemented within the first phase with emergency purposes during flooding and has an average depth of 1.2 m and an area of 350 ha. Phase II, called the Fenéki Pond, was planned to have a total surface area of 57 km², a mean depth of 1.2 m, and water retention time of 90 days. This area should be the recipient of an additional 25–30% nutrient load that originates from the watershed. In November 1992, a 16-km² experimental area of the Fenéki Pond was flooded. Of this area, 90% is covered by macrophytes, primarily reeds. Phase II is planned to be completed by 2012.

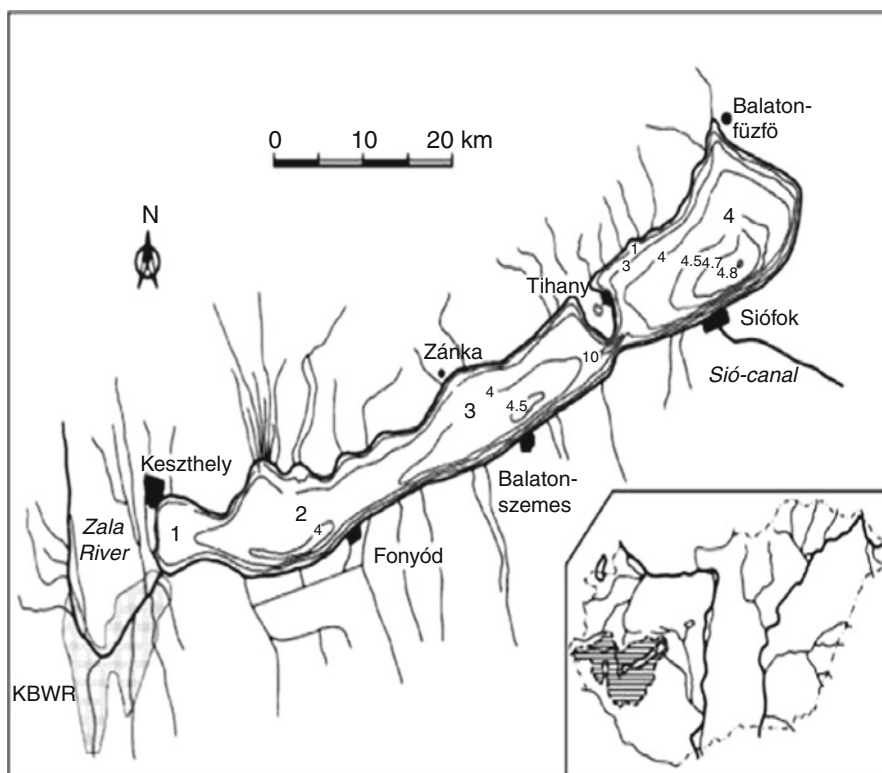
History of nutrient load reduction

A series of management measures decreased external nutrient loads of Lake Balaton by about 50% (Table 2) (Istvánovics et al., 2007; Tátrai et al., 2000, 2008). Loads from point sources were reduced by sewage diversion from about two thirds of shoreline settlements in the period 1983–1986 (all along Basin 4 and along the southern shores of Basin 3) and by introducing P precipitation in large sewage treatment plants of the catchments (including the largest city with 60,000 inhabitants; 1991). Management of diffuse loads was credited to the KBWPR in

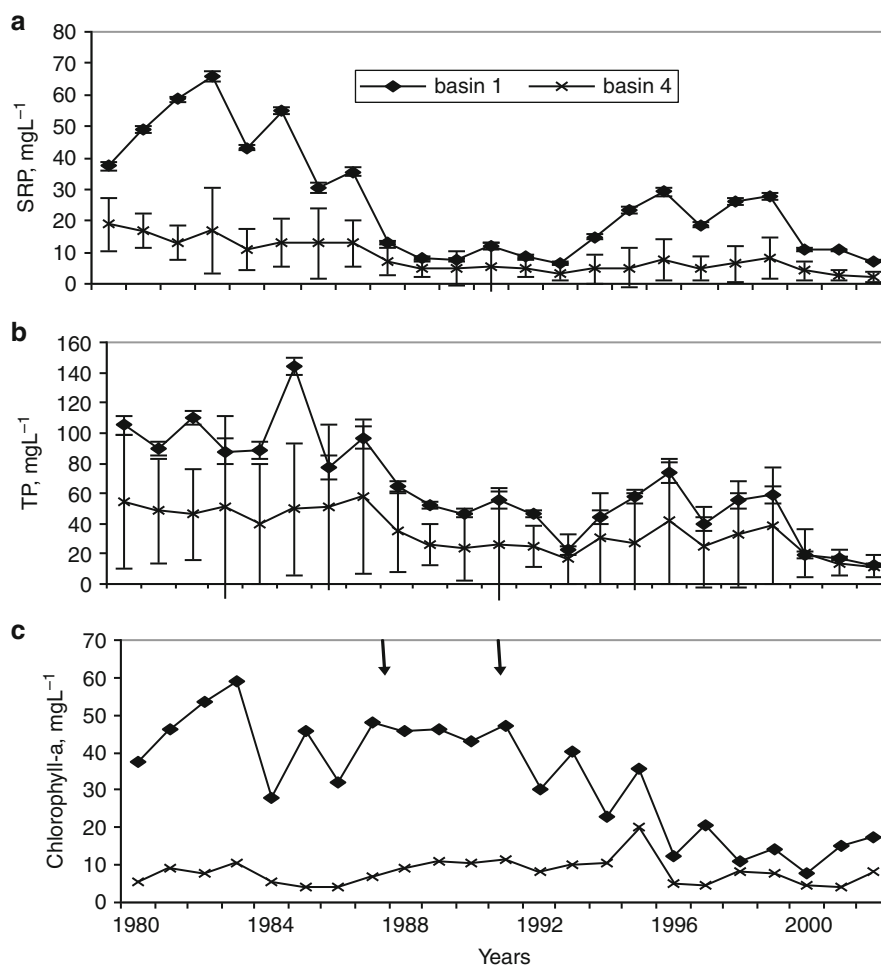
the lower Zala River (Figure 4). By 1988, Phase I of the KBWPR has developed into a hypertrophic reservoir with a reasonable efficiency of nutrient retention (on average, 27%; Istvánovics and Somlyódy, 1999). A part of the Lower Reservoir (Phase II) was opened in November 2002. In this area, dense reed stands retain mineral nitrogen and particulate forms of nutrients with efficiencies over 90% but release 2–10 t of soluble reactive phosphorus (SRP) each year. In addition to the management measures, incidental events also contributed to the reduction in nutrient loads. Fertilizer application dropped to one tenth of the former level in 1989 when Hungarian agriculture collapsed and no recovery occurred yet.

Kis-Balaton and Its Effect on Lake Balaton Water Quality, Table 2 Loads of total P in the pre- (1980–1988) and post management (1989–2002) periods (After Clement, 2000)

Basins	ton P year ⁻¹		g P m ⁻² year ⁻¹	
	1980–1988	1989–2002	1980–1988	1989–2002
1	96	43	2.53	1.13
2	78	44	0.54	0.31
3	46	25	0.25	0.13
4	48	26	0.21	0.11
Total	268	138	4	2



Kis-Balaton and Its Effect on Lake Balaton Water Quality, Figure 4 Map of Lake Balaton showing the reconstructed wetland area of the Kis-Balaton Water Protection Reservoir (KBWPR). Numerals indicate the four basins of Lake Balaton.



Kis-Balaton and Its Effect on Lake Balaton Water Quality, Figure 5 Long-term variation in the estimated external and internal loading to Lake Balaton. The average yearly concentrations of (a) soluble reactive phosphorus (SRP) and (b) total phosphorus (TP). (c) Development in chlorophyll a in the western (1) and eastern (4) basins of Lake Balaton between 1980 and 2002 (mean $\pm$ 1 SD). Arrows from left to right indicate function of Phase I and Phase II of the Reservoir system.

Repeated droughts during 1989–1993 and particularly in 2000–2003 decreased surface runoff and diffuse loads to negligible levels. During this period, the maximum summer chlorophyll a values dropped to 18 in Basin 4 and 61 $\mu\text{g L}^{-1}$ in Basin 1 (Table 1). Considering the timing of various management measures, we selected 1988/1989 as a somewhat arbitrary turning point between pre- and post-management periods (Table 2).

Effect of nutrient load reduction on water quality

In-lake mean concentrations of both SRP and TP declined by about 50–60% from the pre-management (1980–1988) to post-management period (1989–2002). Concentration of TP was primarily determined by sediment resuspension. The reduction of the external and internal P loading had altered trophic responses. The most pronounced effects of reduced nutrient loading were found for

phytoplankton. The annual average chlorophyll-a concentration within few years decreased by nearly 20% during the early post-management period. While interannual fluctuations remained substantial, the mean chlorophyll a concentration in Basin 1 decreased steeply following 1995. A similar decrease after some delay could also be observed in the other basins of the lake. We found some indication of reduced fish predation on crustaceans. The yearly mean ratio of cladoceran was higher by 10% in the post-management period as compared with the pre-management one without any changes in species composition of cladoceran. This change occurred in concert with the reduction in the fish stock by fishery and angling (Tátrai et al., 2008) (Figure 5).

A reduction in the external and internal P loadings resulted in improvement of the water quality 10 years following first intervention, even in the hypertrophic western

part of Lake Balaton (Istvánovics and Somlyódy, 2001) Enhanced internal P loading after the reduction in external nutrient load is clearly an important factor explaining the duration of recovery in shallow lakes. As the mobile P content of the sediments today approaches a new steady state and former species assemblages have reappeared to replace Cyanobacteria during summer, we may expect a long-term stability in water quality of Lake Balaton. Lakes with many years of high P loading can develop a P surplus, where the supply of soluble P exceeds demands of phytoplankton and a large portion of TP occurs in the dissolved form. In Lake Balaton, a substantial decline in chlorophyll *a* occurred at decreasing SRP concentrations at yearly mean concentration around $20 \mu\text{g L}^{-1}$ following the first management measure during the post-management period, a decrease in, first and foremost, the internal loading.

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Cross-references

[Balaton Lake in Hungary](#)
[Lake Restoration](#)
[Nutrient Balance, Light, and Primary Production](#)
[Phosphor Exchange Sediment-Water](#)
[Võrtsjärv Lake in Estonia](#)

LADOGA LAKE AND ONEGO LAKE (LAKES LADOZHSKOYE AND ONEZHSKOYE)

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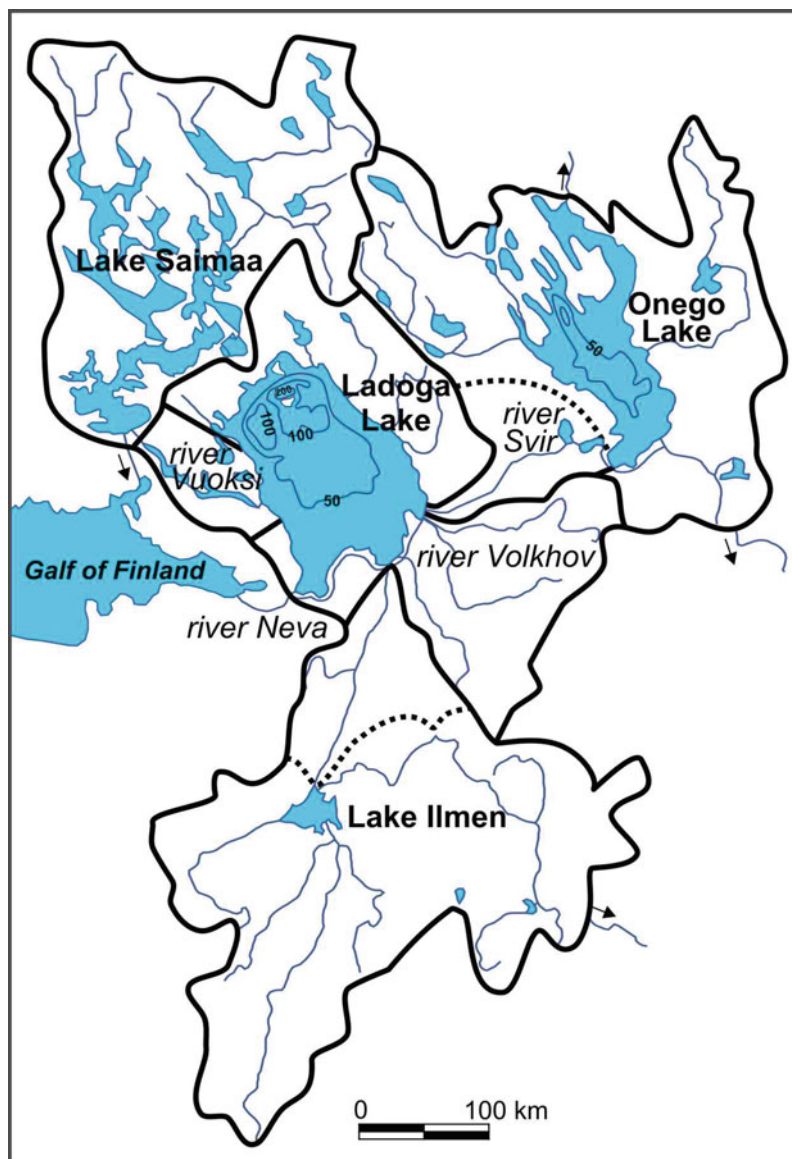
Introduction

Lake Ladozhskoye and Lake Onezhskoye (Ladoga and Onego, respectively; Onego on the contrary river Onega in Archangelsk Region) are the greatest lakes in Europe. Ancient names of Lake Ladoga are Nevo, Al'desk, Al'da, Al'dagas, Al'doga, Al'dagen, Aldea, and Veniemmeri. In ancient times, Lake Onego was called Anizskoye from Finnish name *Ääninen järvi*, *ääni* means voice or sound. These European lakes were called the Great because their dimensions are larger than of any other lakes in Europe (Gusakov and Petrova, 1987; Rukhovets and Filatov, 2010). Lakes Ladoga and Onego located between 58°54'–61°47'N and 60°55'–62°55'N, respectively, are of the northernmost lakes among the world Great lakes. These lakes with river system represent the unified lake system. Lake Onego is connected with Lake Ladoga via River Svir, Lake Saimaa via River Vuoksi (Burnaya), and Lake Il'men via River Volkhov (Figure 1). Lake system is linked with Gulf of Finland in the Baltic Sea via River Neva. The surface area of Lake Ladoga is 17,891 km², average depth is 51 m with a maximum of 230 m, and volume 908 km³; it ranks among the top 15 world's freshwater lakes (Chernjaeva, 1966) (Another dimensions published by (Naumenko 2001)). Lake Onego surface area is 9,600 km², average depth is 30 m with a maximum

of 120 m, and volume 292 km³. The watershed of Great European Lakes is 258,500 km² which extends through North-western European Russia (80%), the eastern part of Finland (19.9%), and Byelorussia (0.1%). The watershed includes the large lakes Il'men and Saimaa. Lakes Ladoga and Onego are an important link in the Caspian-Baltic-White Sea waterway system. Ladoga and Onego are also a key section in the drainage basin of the Baltic Sea. The catchment is made up of four secondary watersheds: Ladoga (28,400 km²); Onego-Svir (83,200 km²); Saimaa-Vuoksi (66,700 km²); and Il'men-Volkhov (80,200 km²) watersheds (Rumyantsev and Drabkova, 2002).

The system of Great European Lakes was generated between contrasting crystalline Fennoscandian (Baltic) shield and Russian plates composed with Paleozoic rocks. In the area of crystalline shields, the ancient Earth rocks granites and gneisses are found at the surface with age of up to 2 billion years. The history of Ladoga and Onego Lakes development is linked with the initial stage of the Baltic Sea formation – the Baltic system of near-glacial lakes. After complete release from glacial cover about 4.5 thousand years ago, the northern shores of the lakes underwent the isostatic rise, which continues with low rate up to date. At the end of Pleistocene, pre-Ladoga and pre-Onego were oligotrophic cold water bodies (Davidova and Subetto, 2000). Nearly 4–5 thousand years ago, the formation of modern Baltic Sea practically was completed. The Neva River, 74 km long, became the only outflow from Lake Ladoga to the Baltic Sea with the average discharge equaled to 2,500 m³/s. The final formation of the Neva River and the whole system of Great European Lakes were formed less than 2,000 years ago. By this time, Lake Ladoga level attained the modern magnitudes (about 4–5 m above the sea level).

The peculiarities of the evolution and generation of Ladoga and Onego Lakes' basins and watersheds had



Ladoga Lake and Onego Lake (Lakes Ladozhskoye and Onezhskoye), Figure 1 Lakes Ladoga and Onego and their watersheds.

created such specific features of the coast line as its high embayment in the north and regular smoothness in the southern, southeastern, and southwestern parts. A high degree of similarity is observed in the northern parts of the Lakes coasts – a large amount of narrow long coves, bays, and fjords, elongated from North to South or from North-west to South-east, and existence of skerries. Ladoga and Onego Lakes in general are very similar to Great American Lakes in their origin, coasts types, bottom relief, and the contrast between the northern and the southern parts of the basins. Lake Onego is the upper one in the system of Great European Lakes.

Since 1933 after the construction of Belomorsko-Baltyisk Canal, Lake Onego was connected with the

White Sea and joined the united system, linking the White, the Baltic, and the Caspian seas. In 1953 on the River Svir (length 224 km), an Upper Svir (Verhnesvirskaya) hydropower station was constructed, since then the lake water regime was regulated and the Upper Svir reservoir was formed. Now, two large hydropower plants operate on the Svir River.

The climatic regime within Lake Ladoga and Lake Onego watersheds could be characterized as transitional one from marine climate to continental. The region is referred to the Atlantic-Boreal region of moderate climatic zone. Prevailing air masses of Atlantic and Arctic origin is typical here all through the year. In average, 550–750 mm of precipitation is registered here. The winds of southern,

south-western, and western directions prevail in the region. Mean annual air temperature varies from 0°C in the north to 3°C in the south. The coldest month is January (with average temperatures –12°C, –13°C in the northern part and –9°C, –10°C in the southern part). A year's warmest month is July (14°C, 15°C in the northern part and 16°C, 17°C in the southern part).

Lakes Ladoga and Onego are completely covered with ice during cold winters; in warm winters, the ice covers only part of lakes. Beginning of ice formation takes place in the middle of November. Ice cover thickness on lakes can reach 1 m and even more in some years. On Lake Ladoga during winter period, quasi-steady polynya exists, dividing ice cover of the coastal area (fast ice) and central part of the lake. Lakes Ladoga and Onego ice cover destruction usually takes place in May, but in cold spring, floating ice may be observed in June. Important characteristics of lakes' thermal regime according to many years of observations (Rumyantsev and Drabkova, 2002) correspondingly are spring thermal bar arise in Lake Ladoga on May 1, in Lake Onego on May 10, and autumn thermal bar correspondingly in the middle of October–November.

These lakes belong to the dimictic type of lakes, where the complete mixture of water body takes place twice a year – in spring and in autumn. The large catchment area located in different landscapes determines the wide diversity of natural and anthropogenic factors affecting the lake ecosystem dynamics. The considerable dimensions of the lakes and slow water exchange (the ratio of the lake volume to annual inflow), that is the retention time for Lakes Ladoga and Onego, is 12 and 16 years, correspondingly. These are the reasons of ecosystem conservatives. Complicated morphometry of the lake basin and its large proportions define heterogeneity of hydrophysical, hydrochemical, and hydrobiological processes in different parts of water body. The variability of limnetic parameters, typical for the deep large lakes, is especially intensified under the heavy and essentially always nonuniform anthropogenic impact.

Water balances of the lakes in km³ for Lake Ladoga and Lake Onego correspondingly are: river discharge to lake 72.3 and 16.8 and precipitation–evaporation 3 and 1.8. Annual amplitude of water level fluctuations are 70 cm (Lake Ladoga) and 75 cm (Lake Onego) (Gronskaya, 2008). The aquatories of these Lakes were divided into four limnetic zones (Rumyantsev and Drabkova, 2002; Rukhovets and Filatov, 2010), each of which plays a special role in ecosystem functioning.

The cyclonic type of circulation (currents) of waters dominates at these lakes. In winter in these lakes covered completely or partially by ice, the circulation of water is very weak (less than 2 cm/s), and the maximum current speed in summer is about 70–100 cm/s.

The phosphorus concentration in these lakes limited the lake productivity level, which accelerated the beginning of the next phase of anthropogenic eutrophication.

Lake Ladoga is a mesotrophic with a low alkaline neutral water and slightly alkaline bicarbonate class of Ca group lake. (In the region of Sortavala town it is eutrophic, of

satisfactory state). By the level of development phytoplankton state in 1960, Lake Ladoga was a typical oligotrophic lake with low level of bacterioplankton which was relatively uniformly distributed over the water basin. By late 1970s, the level of phytoplankton and bacterioplankton development increased significantly. Macrophytes–108 species; phytoplankton–380 species including *Bacillariophyta*–154, *Chlorophyta*–126, *Chrysophyta*–14. Zooplankton has more than 380 species. The main groups are rotifers (*Rotatoria*), protista (*Protozoa*), cladocerans (*Cladocera*), and Copepods (*Copepoda*). These species are mostly inhabitants of the pelagic zone. In the coastal zone, the abundance (tens of thousands in 1 m³) of indicators of polluted water was noted – indicators of significant quantities of organic matter (*Brachionus calyciflorus*, *Keratella cochlearis*, *Polyarthra dolichoptera*, *Asplanchna priodonta*, etc.). Macrozoobenthos together with the meiobenthos organisms and about 600 species invertebrates live at the bottom of Lake Ladoga. In profundity of the open part of aquatory, *Oligochaeta* created 55–80% of the biomass of biocenoses at the bottom. Lake Ladoga is inhabited by more than 50 fish species (Rumyantsev and Drabkova, 2002). Only 10 species have the most economical importance: whitefish, smelt, perch, roach, pikeperch, vendace, bream, pike, salmon, and ruff. The Red Book of Russia includes the Siberian sturgeon and Volkhov whitefish. General fish catches in the 1950s ranged from 1,500 to 6,700 t in a year. In average, it made 5,000 t per year. During the past decade, stocks of lake-river fish, as the Volkhov whitefish, salmon, and trout (lake trout) have strongly decreased. And during the years 2003–2009, the annual catch was 622 t per year. The state of the Ladoga seal population is good enough; the total number of seals is estimated at about 5,000 individuals.

Lake Onego is oligo-mesotrophic with water which has the same characteristic as the water of Lake Ladoga. Water in Lake Onega has better quality than water in Lake Ladoga.

Bacteriocenoses on the lake aquatory are characterized by high variability of its features. Macrophytes are presented by 75 in the lake. Phytoplankton of Lake Onega includes 780 species. These species are: *Bacillariophyta*–390, *Chlorophyta*–203, *Chrysophyta*–78, and *Cyanophyta*–63. Zooplankton of Lake Onego has similar features to the zooplankton in Lake Ladoga. It contains 254 species: *Rotatoria*–123, *Cyclopoida*–29, and *Cladocera*–82. Lake Onego contains more than 500 species and forms of macrozoobenthos, which are mostly concentrated in the coastal zone. Outside coastal zone, it is mainly represented by four groups: *Oligochaeta*, *Amphipoda*, *Bivalvia*, and *Chironomidae*. Ichthyofauna in Lake Onego is similar in general to that of Lake Ladoga. Though salmon inhabits Lake Ladoga, its fishery is significant in Lake Onego only. In Lake Onega, 16 species of fishes are considered as marketable fish, such as salmon, lake trout, palia, vendace, whitefish of various ecological forms, grayling, smelt, perch, burbot, pike, roach, perch, ruff, bream, ide, and ablet. Endangered species include sturgeon, sabrefish, and catfish. Vulnerable species include lake

salmon, trout, grayling, and the category of rare and so far safe species – various ecological forms of whitefish.

Until the mid 1960s, industrial activities on the watershed influenced very little on the state of the ecosystem and the water quality in Lake Ladoga. The Lake preserved its status of an oligotrophic water body, as it had at the beginning of the twentieth century. Insignificant bacterial pollution was registered only in the vicinity of the waste water outlets of the paper mill enterprises. The anthropogenic load of phosphorus (P) on Lake Ladoga, the origin of the lake eutrophication, has increased since the early 1960s. Until the mid-1980s, the average phosphorus concentration, P_{tot} , reached 28 $\mu\text{g P/l}$, changing the lake status from oligotrophic to mesotrophic (Rumyantsev and Drabkova, 2002). The economical collapse in Russia in the 1990s led to a certain decrease of the phosphorus load on Lake Ladoga (from 6,100 t P/year in 1984–1995 to 4,000 t P/year in 1996–2003). The anthropogenic load on Lake Onego in 1970–1986 resulted in the evolution of the lake trophic status from oligotrophic to mesotrophic only in semi-closed bays. In the last 15 years, the lake as a whole has retained its oligotrophic status. Currently, P_{tot} in the lake is 8–10 $\mu\text{g P/l}$. Lake Onego is now at the stage of ecosystem destabilization and in the initial phase of eutrophication. The phosphorus load on Lake Onego changed from 1,003 t P/year in 1992–1997 to 786 t P/year in 2001–2002.

Several numerical experiments were performed by means of mathematical model for the determination of admissible phosphorus load which preserves the ecosystem stability. This load turned out to be 4,000 t P/year (Rukhovets and Filatov, 2010). These experiments reveal that Lake Ladoga would preserve its weakly mesotrophic status. In a case where the initial higher load would be decreased to 4,000 t P/year, the lake returns to a weakly mesotrophic status in 5 years. For Lake Onego, simulations of the lake ecosystem functioning under a different type of phosphorus load showed that the load of 800 t P/year and 15,000 t N/year is the most desirable for the lake ecosystem stability.

Economic development in the region of the Great Lakes of Europe is at a very high level. There operate numerous extracting and processing industries, most of them water- and resource-intensive, such as pulp-and-paper mills, oil refineries, chemical plants, wood processing, non-ferrous metal processing and food industry enterprises, hydropower and heat power plants, building material industries, etc. The region possesses mineral, forest, and balneological resources. During Soviet times, agriculture was quite well developed. It is now gradually recovering, but application of fertilizers – sources of nutrient pollution – has dropped several times. Lake Ladoga catchment area has a population of 3.5 million people, including 2.7 million urban residents. Population density in the Russian part of the catchment is 12.4 person/km². Agricultural areas cover 11% of the area. Several hydropower plants operate on a number of rivers in the catchment (Rumyantsev and Drabkova, 2002). In 2006, water withdrawal from the lake catchment amounted to ca. 1,500,000 m³, of which about 750,000 m³ were

utilized by St. Petersburg communal facilities (Rukhovets and Filatov, 2010). Intensive economic development results in substantial human impact on water objects, which is made up of effluents from industries, communal facilities (point sources), fish farming, and agriculture, as well as dissolved and suspended impurities from arable land, pastures, and fertilized and abandoned land (non-point sources or diffuse loading), which are the main causes of pollution and eutrophication of the water bodies. The greatest hazard for the lake ecosystems among point sources is direct wastewater discharges. The important changes have taken place in the past few decades in the issue of water protection from wastewater impact.

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Cross-references

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LAKE ICE

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Introduction

Millions of inland water bodies freeze over each winter. In February, the total extent of lake ice cover in the Northern Hemisphere probably exceeded 2 million square kilometers,

in over 50 countries. On both hemispheres, there are also lakes which are perennially frozen; the summer thickness of ice is in excess of 5 m in some Antarctic lakes. The extreme case is Lake Vida, which has 19 m of ice overlying a brine with a salinity seven times that of seawater (Doran et al., 2003). High mountain lakes may have permanent ice cover even in the equatorial zone.

In North America, seasonal lake ice cover can develop as far south as 33°N, in Eurasia 26°N. Among the 15 largest lakes on the Earth, only four are not affected by ice (Prowse et al., 2007). In high mountains, freezing lakes occur in a wide range of latitudes.

Unlike river ice, lake ice is virtually unaffected by man's actions in watercourses and river basins. Only exceptionally do, e.g., thermal effluents, a road embankment, or heavy regulation alter lake ice conditions. Thus nature's fingerprint in lake ice is very pure – a fact which offers many possibilities in climate change research.

Trends in lake ice variables

Many factors have an influence on lake ice formation, growth, and decay. They can roughly be divided into climatic, hydrological, morphometric, and chemical. Of these, the morphometric ones are most stable, having typically very slow rates of changes. The most important chemical factor is the salinity of water, which also rarely undergoes rapid fluctuations.

As to the hydrological factors, a strong throughflow can completely inhibit the formation of ice cover. The factor playing a most important role – and affecting all lakes – is, however, a climatic one: the air temperature. Statistically, it has, e.g., been found to explain up to 60–80% of the variance in the breakup dates of lakes (Livingstone, 1997; Williams et al., 2004; Korhonen, 2005). Therefore the timing of ice-on and ice-off has been modeled in numerous studies on the basis of air temperature alone, and the reverse; historical variations in lake ice phenology have been used extensively as a proxy for ambient air temperatures.

In the widely cited study of Magnuson et al. (2000), the freezing was found to have delayed on the average by 5.7 days per 100 years in a sample of large lakes in the Northern Hemisphere, whereas the breakup had shifted 6.3 days toward an earlier date. Comparable results have been obtained in numerous other studies from North America, Europe, and Asia (e.g., Latifovic and Pouliot, 2007; Franssen and Scherrer, 2008; Punsalma et al., 2004).

In Figure 1, the freezing and breakup dates of Lake Kallavesi in Finland are shown in data series, which cover 177 and 189 years, respectively. Linear trends indicate significant changes toward later freezing and earlier breakup; the duration of ice cover has shortened by almost 1 month. The change seems to have accelerated in the last one and a half decades, although this signal is not very clear yet.

The effect of teleconnections on ice phenology has been demonstrated in several studies. Both Southern Oscillation (ENSO/SOI), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO) have left a signal to many

North American lakes (e.g., Ghanbari et al., 2009), the NAO to the lakes of Europe and northern Asia (e.g., Yoo and D'Odorico, 2002).

There is evidence that the sensitivity of freezing and breakup dates is highest near the southern limit of lake ice formation. For example, Weyhenmeyer et al. (2005) found the breakup date to shift around 14 days earlier per 1°C rise in air temperature in southern Sweden, but only 4 days per 1°C rise in northern Sweden. The durations of the ice cover are 0–125 days and 200–250 days, respectively. In many lakes near the southern limit of ice regime the frequency of ice-free winters has already increased. For example, in the 186-year record of Lake Champlain in Vermont, almost half of the 31 winters when the lake has not frozen over have occurred since 1970 (Wake, 2005). Similar development has been reported from Lake Windermere in the English Lake District (George, 2007), from the lakes in the Netherlands (Mooij et al., 2005) and on the Swiss plateau (Franssen and Scherrer, 2008).

The thickness of lake ice correlates much more poorly with air temperature than the freezing and breakup dates. The maximum thickness is not a measure of the severity of winter, but rather a complicated function of snowfall and air temperature patterns. Even with exactly similar negative degree-days and snowfall totals, the maximum ice thickness may vary considerably. However, in some studies numerical estimates have been calculated; e.g., according to Williams et al. (2004) the maximum ice thickness would be reduced by 7 cm per 1°C rise in mean annual air temperature.

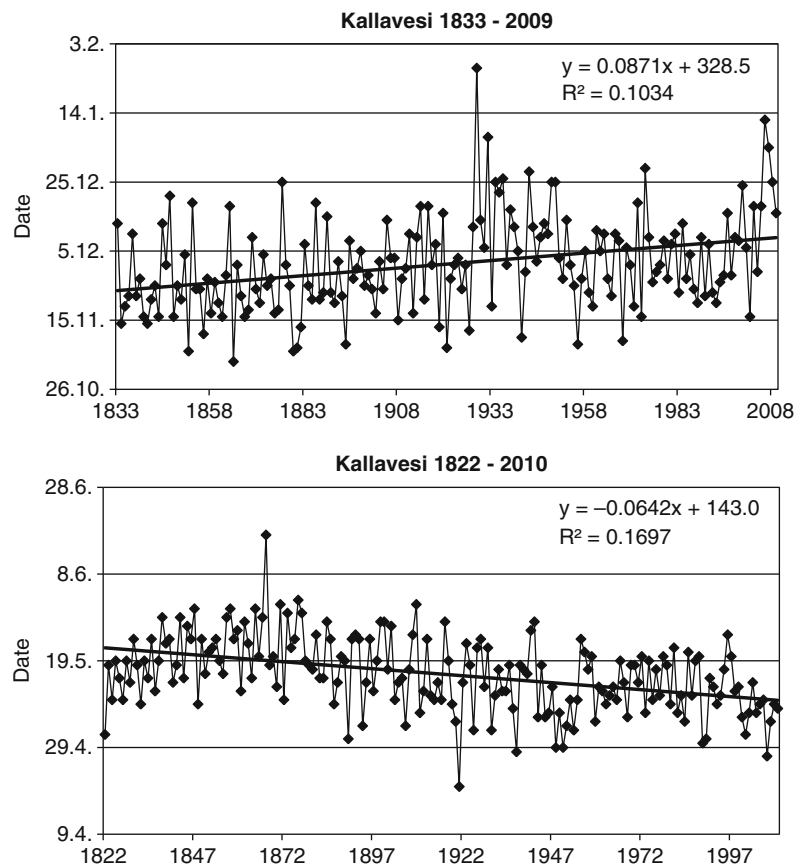
Several long time series of lake ice thickness are available in Finland. Some series from observation sites in southern and central Finland have indications of a thinning trend, some in the northern Finland of a thickening trend until 2002 (Korhonen, 2005). In recent years, lake ice has been relatively thin in the north, and, e.g., for Lake Inari the fitting of two regression lines with a turning point at 1972 seems to be more appropriate (Figure 2). However, no firm conclusions can be drawn.

The effects of ice on the lake water balance

The onset of ice cover greatly reduces the energy fluxes between the lake and the overlying air. One consequence is a sharp decline in lake evaporation. If a lake stays free of ice cover, evaporation may continue at a high rate and even increase.

In spring the surface water of a lake starts to warm after the breakup date, with a consequent increase of evaporation. For example, in Lake Pyhäjärvi in southwestern Finland the evaporation in May in 1936–1973 was estimated to range from 8 to 81 mm, largely depending on the breakup date (Kuusisto, 1975).

As long as the control section at the lake outlet remains ice-free, floating ice cover does not have any influence on the outflow from the lake. Particularly in small and shallow lakes, the control section will be partly or completely ice-covered, with a consequent reduction in outflow.



Lake Ice, Figure 1 Time series of the freezing and breakup of Lake Kallavesi in eastern Finland. According to the linear trends (significant at the level of 99.9%), the freezing date has shifted 15 days later in 1833–2009, while the breakup date has shifted 12 days earlier in 1822–2010.

In the Finnish network of 250 discharge stations, 95 are located at lake outlets without artificial structures. In a severe winter, around 60 of these lake outlets have ice cover, in a mild winter only 40. In those, the outflow is typically 20–50% of that in the ice-free conditions.

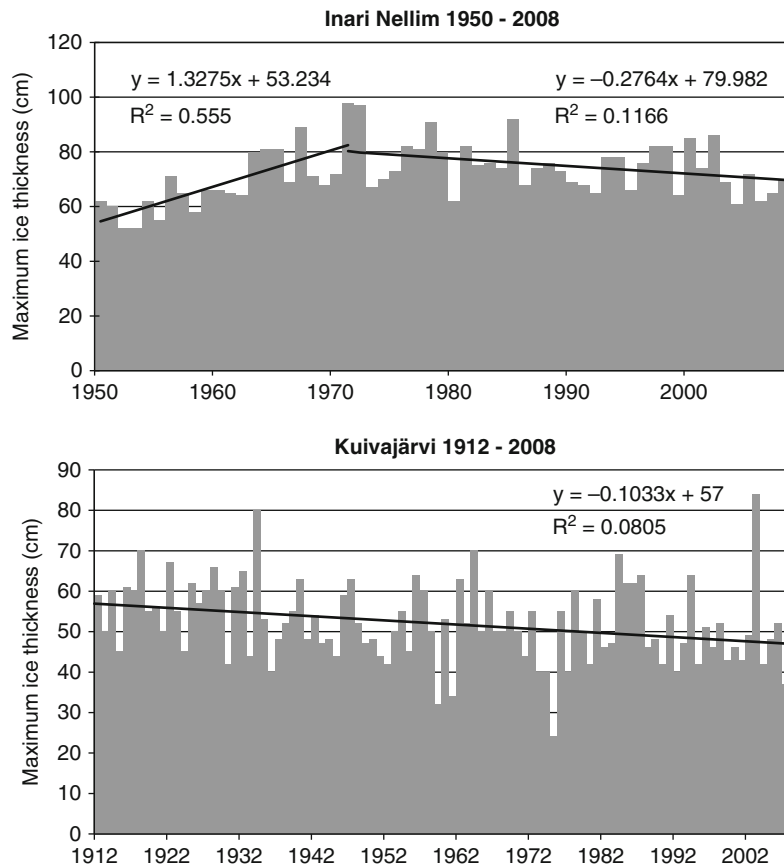
As a consequence of rising air temperatures, the ice cover at lake outlets will become thinner or even disappear. At the same time, inflows into the lakes will increase. Together these factors may lead to a considerable enhancement of winter outflows from the lakes.

In the vicinity of large lakes, the ice cover – or better the lack of it – has a well-known influence on snow storms. When cold air passes for long distances over relatively warm waters of a large lake, moisture and heat are picked up and huge amounts of snow may fall on downwind shore. In the Great Lakes region, heavy lake-effect snowfalls occur along the southern and eastern shores of particularly Lakes Superior, Erie, and Ontario (Delcourt et al., 2002). For example, in the winter season of 1976–1977, the total snowfall in Hooker, New York, was 1186 cm with a period of over 50 consecutive days with snowfall (Heidorn, 1998).

Climate change may increase the severity and frequency of lake-effect snowstorms, because open water conditions in winter months will probably become more prevailing in many northern lakes. The phenomenon may also be created over some lakes, where it is unknown at the present climate. These may include the largest lakes in the Finnish Lake District.

Some ice is immobilized on the shallow areas of the lake during winter. This effect can be particularly pronounced in reservoirs with a high drawdown, leading to a loss of release capacity and the amount of electricity produced. At the Gouin Reservoir in Quebec, the immobilized portion represents up to 8% of water available for hydroelectricity production (Seidou et al., 2006).

In the flat northern tundra, there are numerous shallow lakes, which are solidly frozen to the bottom in late winter. For example, on the North Slope in Alaska, even lakes 2 m deep become solid ice (Kovacs, 1978). Most of these lakes have resulted from the thawing of ice-rich permafrost or the melting of snow and ice, as the frozen ground underneath has prevented the water from draining away. The lakes tend to enlarge because of wave action and



Lake Ice, Figure 2 Time series of maximum ice thickness at Lake Kuivajärvi (60°47' N, 23°50' E) and Lake Inari (68°52' N, 28°16' E). All regression lines shown are significant at least at the level of 95%, but interannual variations are large enough to make all conclusions uncertain. Interestingly, the thickest ice in the whole observation series of Lake Kuivajärvi was observed in the winter of 2002–2003; the same was true at almost all measuring sites in southern Finland.

continued thermal erosion of the banks. Climate warming may enhance these processes and also create considerable greenhouse gas emissions.

Snow on lake ice

Snow falling on the surface of a frozen lake forms part of the water storage. A heavy snow load may substantially increase the outflow from the lake in winter months. In a sample of 45 unregulated Finnish lakes, a water equivalent of 50 mm of the lake snow cover increased the outflow on the average by 19% in February (Kuusisto, 1994).

Despite the smoothness of the ice surface, the areal variability of the lake snow cover is often high. This variation is mainly due to the uneven formation of snow ice and the transport of snow by wind. Snow ice tends to form more extensively near shores and congelation ice more extensively in central parts of lakes (Bengtsson, 1986).

Snow cover effectively blocks the penetration of solar radiation into the water mass. Petrov et al. (2005) studied in northwestern Russia a lake with 20–40 cm snow cover. They found the radiation flux at the lower boundary of ice

to be only around 0.2 W m^{-2} in the presence of snow, while the flux increased to $2\text{--}20 \text{ W m}^{-2}$ in mid-April and up to $50\text{--}120 \text{ W m}^{-2}$ in late April.

Lake ice as a nuisance and as a benefit

Lake ice has a multitude of effects both for nature and human activities. The functioning of the lake ecosystem is essentially linked to the freezing and melting cycle. Stratification and mixing of the water mass, exposure to solar radiation, and all energy and gas exchange with the atmosphere depend critically on the presence of ice cover.

Until recently, the winter conditions of ice-covered lakes were considered rather static. This was mainly due to the low research activity; now the interest in various processes in under-ice environment has grown rapidly. It has turned out that variations in weather conditions, particularly those preceding the time of freezing and breakup, may have important impacts for hydrodynamics and consequently to microorganisms and further to higher trophic levels (Salonen et al., 2009).

The thermal expansion of ice is a powerful geomorphic agent on the lakeshores in cold regions. It also causes often

damages to manmade structures. The cracking of ice at the onset of cold spells is a common feature, too, leading to risks for ice traffic. It has even been found to induce harmful vibrations and noise in buildings near the shoreline (Makkonen et al., 2010).

The shortening of the ice cover season as a consequence of rising air temperatures can lead to profound changes in, e.g., biological productivity and diversity. These changes may vary from detrimental to beneficial. The whole lake ecosystem may collapse. On the other hand, wintertime fish kills, which are frequent in many shallow ice-covered lakes, may be eliminated.

For human activities, lake ice is both a nuisance and a benefit. It may hinder transportation by boats and ships, but an opening of an ice road may become possible with the growth of ice thickness. It ends some fishing activities, but creates possibilities for new ones. Wintertime recreation on ice is a common habit in all circumpolar countries. Unfortunately, it can also lead to fatal accidents. For example, in winter 2007–2008, when lake ice in southern Finland was thinner than in any other winter during the last 100 years, over 30 people drowned. It was even discussed that legislative measures might be needed in the future – in some central European countries it is already forbidden to go to lake ice.

Particularly in the eighteenth and nineteenth centuries, the lake ice was also used extensively for cooling purposes. Still in the childhood of the author in the 1950s, most farmers in his village in central Finland had a storage of lake ice covered with sawdust. Some pieces of ice were dug out every day to cool milk containers in a water-filled tank.

The future of lake ice

The sensitivity of lake ice to changing climate has been studied extensively in recent years. Most of these studies are based on empirical relationships between meteorological and ice regime variables. Non-climatic parameters like latitude or lake area have also been used. In general, these relationships have a high statistical significance, if at least several decades of historical data are available.

Can these relationships be used to predict the future of lake ice? In many studies this has been made. However, there is no guarantee that such empirical relationships will be valid in the future, because, e.g., systematic changes in the structure of the energy balance over lakes are possible. Furthermore, increased snowfall may enhance the growth of white ice, which could cause a delay in breakup. Physical lake ice models, involving the use of several meteorological variables, could give more relevant results.

Ground observations related to lake ice have dramatically declined in several countries. This can be partly compensated by remote sensing methods, but there is a risk that many excellent proxy indicators of climate change will be lost.

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Cross-references

[Finnish Lakes](#)
[Ice Formation on Lakes and Ice Growth](#)
[Thermal Regime of Lakes](#)

LAKE MONSTER

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Introduction

There are many monsters reported to be living in many lakes worldwide. Probably, the most famous is the legendary Loch Ness Monster, renowned for over 1,400 years and with over 1,000 sightings during the last 100 years. In recent times, “sightings” have been mainly between the 1930s and the present without any conclusive evidence of a living animal. Loch Ness is some 23 miles (37 km) long, with an average width of about 1 mile (2 km). The average depth of the loch is 470 ft (145 m), with a maximum depth of 754 ft (227 m) more than the mean depth of the North Sea and a volume of 263,000 million ft³ (7,452 million m³). A survey of the loch was undertaken in 1903 by Sir John Murray during his Bathymetric Survey of the Scottish Lochs, 1897–1909. The loch has a catchment area of 770 sq. miles (2,000 sq. km), and the area of the loch is 22 sq. miles (56 sq. km) (see [Figure 1](#) and [2](#)).

Classification of lakes

Lakes may be classified as *eutrophic* (nutrient rich) and *oligotrophic* (nutrient poor), as is Loch Ness. In any lake, the water stratifies in summer. When this occurs, the upper water, the *epilimnion*, warms in the summer and becomes less dense and floats on the colder water below, the *hypolimnion*. The two layers are separated by a zone of sharp temperature change, the *thermocline*. In productive lakes, nutrients in the epilimnion can become depleted by algal growth and cannot be replenished until winter gales mix the two water layers together. Therefore, the algae die back in late summer. At the same time, the decay of organic matter falling through the thermocline robs the hypolimnion of oxygen. In unproductive Loch Ness, very little organic matter falls through the *thermocline* into the *hypolimnion*. There is, therefore, sufficient oxygen for life in even the deepest parts of the loch. The *epilimnion* temperature in Loch Ness rises to about 12°C, but in the depths, the temperature remains at about 5.5°C. However, it is estimated from the many sonar investigations carried out that the fish stock in Loch Ness is of the order of

20 t, perhaps not enough to satisfy a family of predators. The loch supports mainly brown trout, eels from the Sargasso Sea, Arctic char (some living at a depth of some 200 m), and salmon, which come to spawn from their Icelandic feeding grounds. It is estimated that some 20 t of salmon a year pass through the loch, some within a few days, on their way upstream to their spawning rivers.

The formation of Loch Ness

Some 400 million years ago, the folding and crushing of the Caledonian mountains formed a large fault dividing Scotland in half and stretching as far as Newfoundland. The fault is called the Great Glen, which later held Loch Ness. However, before that, the huge Lake Orcadie stretched from the Moray Firth to the Great Glen. Some of the fish at the time evolved into amphibians as the land mass moved in Devonian and Carboniferous times. And it is known that reptiles evolved into dinosaurs. Ten thousand years ago, glaciers retreated up the Great Glen. Ice-dammed lakes broke through in a succession of floods, leaving traces of “parallel roads” on the hillsides. The land, relieved of the ice burden, has since risen to bring the loch to 16 m above sea level. Loch Ness is connected to the sea by the 7-mile-long River Ness along which migratory fish, mainly of the salmon family, have colonized it. Salmon and eels still migrate to and from the sea, and even seals have no difficulty in entering the loch. There is also a man-made canal built by Thomas Telford and opened in 1822, linking the lochs of the Great Glen into a 60 mile (100 km) passage from sea to sea – from the Atlantic to the North Sea.

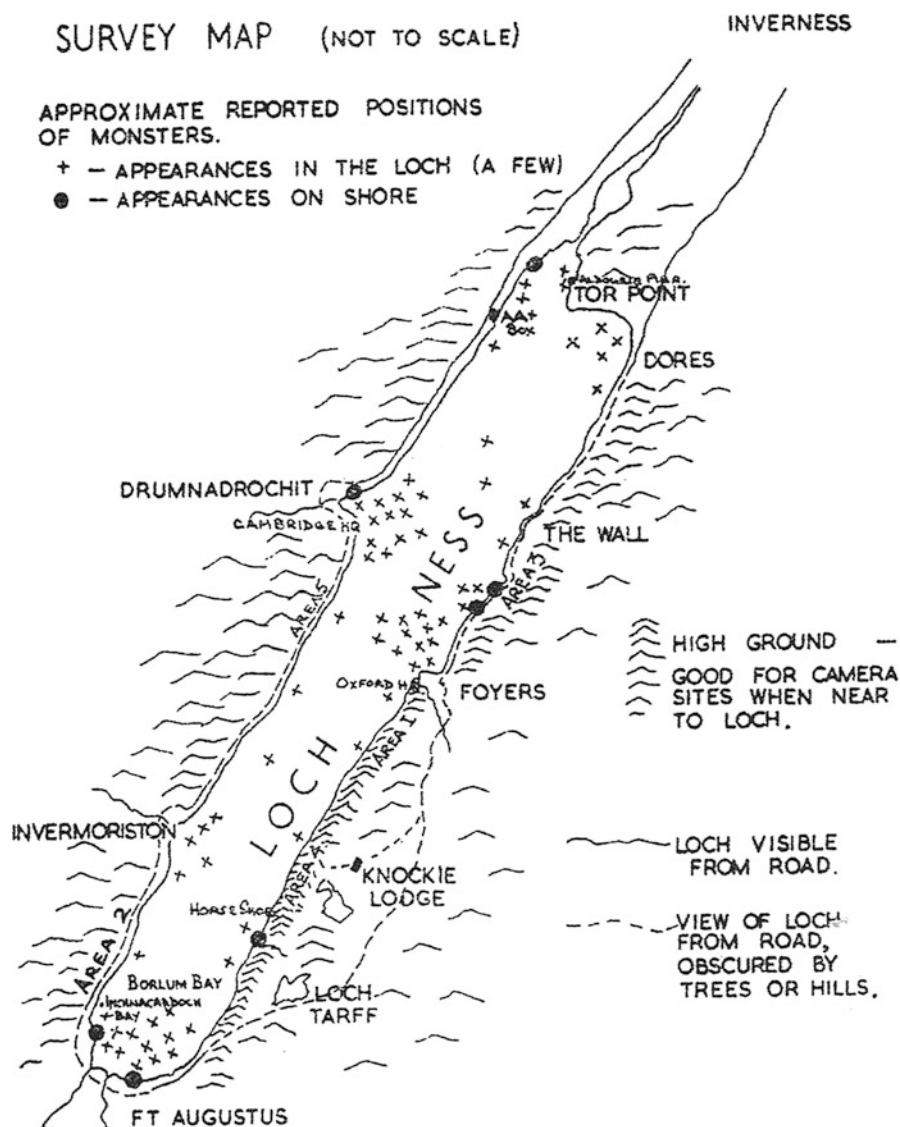
It seems certain, however, that the phenomenon has had a significant effect on tourism and the economy of the area, especially in the case of Loch Ness where thousands of tourists and others continue to descend on the loch in search of “Nessie” (including the author!).

Legendary monsters

Legends have it that “dragons” and “worms” once infested the European countryside, for example, the huge “Worm” displayed in the main square in Klagenfurt, Austria. Legends relate how most of the great heroes – Sigurd, Beowulf, Siegfried, King Arthur, Tristan, St. George, and St. Michael – all slew dragons. Other well-known “Worms” include the Lambton Worm (County Durham); the Lyminster Dragon in Sussex; the Yeti, better known as the Abominable Snowman in the Himalayas; Bigfoot (Sasquatch) (US); Ogopogo in Canada; Swamp Ape; Skunk Ape; and Momo, the Missouri Monster. Like the Loch Ness Monster, none have actually been scientifically confirmed.

Tim Dinsdale

In the sixties, the film made by Tim Dinsdale renewed interest in the Monster. Dinsdale, an aeronautical engineer, was one of the most dedicated Monster seekers and spent 27 years in its search until his death in 1987. He published several books on the Loch Ness Monster.



Lake Monster, Figure 1 Map of Loch Ness.

"Sightings" of note of the monster since 1933

In 1933, on July 22, Mr. Spicer, while driving along the road between Dores and Inverfarigaig, was surprised to see a "large animal" crossing the road in front of him and suddenly disappearing into the loch about 30 m away.

Also in 1933, a Mr. Hugh Gray reported "a large animal in the loch about 12 meters away" near Foyers.

Again in 1933, on December 12, Malcolm Irvine and colleagues filmed "the monster" on the loch near Inverfarigaig. In November, Lt. Commander Rupert Gould conducted an analysis of the sightings so far. He described 42 sightings from the period May 1923 to May 1933. Gould suggested an airship might be useful to search and investigate the monster, but the suggestion was never taken up.

On January 5, 1934, near Abriachan, a Mr. Grant, a motor cyclist returning home from Inverness, almost collided with a "large animal" about to slip into the loch.

On June 5, 1934, the famous surgeon's photograph showed what appeared to be a large elephant-like animal (the surgeon was actually Dr. Robert Kenneth Wilson, a London gynecologist). The photograph was only exposed as a hoax at the Loch Ness Centre 60 years later.

One of the best descriptions came from a maid early in the morning of June 5, 1934, in Fort Augustus as she looked out of a window where she worked. She reported "a giant animal with a long neck, small head and elephant skin with two short forelegs." She was about 200 m from the loch and watched the animal for at least 20 min.



Lake Monster, Figure 2 Loch Ness from Drumnadrochit (January 2009).

In 1935, a Dr. McRae claimed to have filmed the Monster with his cine camera for some 5 min. It had “a long neck, a pointed head, small horns and three humps and was about 9 m long.” As a matter of interest, this film is said to be safely in a London bank vault.

During the 1939–1945 war, Loch Ness was under the control of the Navy, and little or no sightings were recorded. Any sightings during the war may be found in the UK Archives in Kew, London. Nevertheless, in May 1943, one of the officers, C.B. Farrel, of the Royal Observer Corps reported a “sighting” of what he took to be the Monster.

In 1952, John Cobb was killed on the loch when his jet-powered boat *Crusader* disintegrated in attempting the world water speed record. The tragic accident was believed to have been caused by sudden unexplained ripples, “an area of disturbed water.” The waves were probably caused by one of Cobb’s own boats.

More recent “sightings” in summary (with numbers in parenthesis) have been the following: 1965 (12), 1967 (25), 1971 (11), 1973 (12), 1975 (9), 1977 (17), 1979 (27), and 1983 (23).

Source for above is Ulrich Magin, as published in Bauer, H., 1986 “The Enigma of Loch Ness” University of Illinois Press.

The following records are less reliable: 1992 (1), 1993 (1), 1996 (9), 1997 (11), 1998 (1), 2000 (1), 2001 (1), 2003 (1), 2004 (1), 2005 (4), and 2007 (2).

The Loch Ness Investigation Bureau (LNIB), during surveys, captured on film 4 “sightings” during 1962 and 1963.

Expeditions and investigations

1933: The Daily Mail sponsored investigation.

Sir Edward Mountain Expedition (1934) placed 20 observers around the loch every day for 5 weeks. Eleven sightings were made, including five photographs, but did not provide conclusive evidence.

Loch Ness Phenomena Investigation Bureau (LNPIB 1962–1972) – observations by members, including Sir Peter Scott, Mrs. Constance Whyte, and David James MP.

Oxford and Cambridge Universities team using 28 kHz echo sounders moved together along the length of the loch.

The LNPIB Sonar Study (1967–1968) volunteers and scientists observed large fast-moving animal objects.

Carroll’s Sonar Study (1969) mobile sonar scan made contact with a strong animate echo for 3 min.

Submersible Investigations (1969) *Pisces* sub from Vickers noted large moving object about 15 m above the bed of the loch.

The Big Expedition (1970) hydrophones deployed at intervals throughout the loch noted strange sounds.

In the summer of 1982, The Loch Ness Project spent 1,500 h of scanning sonar patrol. Forty contacts of unusual strength and depth were recorded.

Loch Ness Project: “Operation Deepscan” in 1987 set up a sonar curtain along the loch using a flotilla of 24 motor launches equipped with Lowrance echo sounders (See [Figure 4](#)). Most of the contacts made were from debris. However, three seemed to move. These could have been seals which are known to visit



Lake Monster, Figure 3 Side scan sonar survey vessel on Loch Ness with, from left, Dr. Robert Rines, Mr. Martin Klein, and Mr. Tim Dinsdale.

the loch each year or possibly some form of unrecognized interference between the sonars.

Loch Ness Project 1981, Sonar Survey of Arctic char found living at a depth of 214 m

Robert Rines' Underwater Studies (1972, 1975, 2001) underwater photos using time-lapse cameras appeared to show animals resembling plesiosaurs (see [Figure 3](#)).
Discovery Loch Ness (1993) researched the ecology of the loch.

Global Water Search Team (GUST) Expedition (2001) sonar contact showed movement on the screen.

Monster Hunt Weekend 1990 Media event providing a focus for foreign television crews, including the British ITV children's program *Motormouth* with a four-man Japanese crew, seemed to show a large animate object moving at speed at the bottom of the loch.

By the end of the 1990s, investigations from 20 universities were under way in collaboration with The Loch Ness Project, including the Rosetta Project (1994) concerned with sediment cores. Project Urquhart (1993) was concerned with the biological condition of the loch.

Lakes with "sightings" of monsters

There are some 265 lakes worldwide where monsters have been reported (of which, surprisingly, 24 are to be found in Scotland alone)!

Following is a selection:

Lake Baikal (Siberia)
Bala Lake (Wales)
Bear Lake (Idaho–Utah, USA)

Lake Brosno (Russia)
Lake Champlain (USA/Canada)
Charleston Lake (Canada)
Faymouth Ency (Cornwall, England)
Flathead Lake (Montana, USA)
Fulk's Lake (USA)
Lough Keane (Ireland)
Lake Kenas (China)
Kleifarvatn (Iceland)
Lago Las Rocas (Chile)
Lago Nahuel Huapi (Argentina)
Lake Manitoba (Canada)
Lake Menbu (China)
Lake Mjosa (Norway)
Loch Morar (Scotland)
Lough Muck (Ireland)
Lago Nahuel Huapi (Argentina)
Loch Ness (Scotland)
Okanagan Lake (Canada)
Lough Ree (Ireland)
Seljordsvatnet (Norway)
Lake Simcoe (Toronto, Canada)
Storsjon (Sweden)
Lake Tahoe (USA)
Lake Tianchi (China)
Lake Van (Turkey)
Lake Varota (Russia)

Search pioneers

The legendary search for giant or unusual animals, either aquatic, amphibious, or other species, has interested many

scientists and others over many years, and the search still goes on. Included in this group of pioneers are:

Herodotus (484–425 BC)
 Lucretius (99–55 BC)
 Pliny the Elder (23–79 AD)
 St. Columba (521–597 AD)
 Olaus Magnus (1490–1558)
 Conrad, Gessner (1516–1565)
 Erik Pontoppidan (1698–1764)
 Anton Oudemans (1858–1943)
 Charles Fort (1874–1932)
 Ivan Sanderson (1911–1973)
 Tom Slick (1916–1962)
 Rene Dahinden (1930–2001)
 Bernard Heuvelmans (1916–2001)
 Ted Holiday (1920–1979)
 Tim Dinsdale (1924–1987)
 Grover Kantz (1931–2002)
 Jordi Magraner (1967–2002)
 Adrian Shine investigator since 1973

Location of sightings and assessment

In considering the location of the “sightings” in Loch Ness, the following places seem to have been the most rewarding (see [Figure 1](#)): Urquhart Castle, Urquhart Bay at Drumnadrochit, Foyers, Dores, Achnahane, Invermoriston, Inverfarigaig, and Fort Augustus.

Hoaxes, perceptions, and illusions

Forty years of surveillance has understandably identified possible illusions or misleading perceptions by sincere eyewitnesses, for example, trees, boats, mirages, logs, deer, wind slicks, and seiches. There have also been hoaxes. One such hoax, related to that mentioned above, is the famous “surgeon’s photograph,” the hoax finally proved by the Loch Ness Centre. Others may have been the result of wishful thinking. However, by far, most of the 1,000 documented sightings of the monster have been made by honest observers who did not seek publicity.

Hypothetical candidates

Adrian Shine of the Loch Ness Project, in his book “Loch Ness,” discusses what animal could survive undetected in a loch too cold for reptiles to reproduce. Some have suggested large eels which did not return to the sea to spawn and instead grew to a huge size. Shine also considers the huge predatory European catfish, the wels. The loch is too cold for them to reproduce, but a single specimen introduced by man could live for a 100 years and so be present for the entire period of the modern sightings record. He also considers the Atlantic sturgeon, one of which was caught in the River Towey in Wales in 1933 and another off the canal entrance in 1871. Indeed, in 1932, a Miss MacDonald saw a crocodile-like creature swimming up the River Ness. Could this have been one of the legendary kelpies (Gaelic, *Each Uisge*) or Water Horses of folklore or even an actual sturgeon? A small

Siberian sturgeon was used in an experiment in a pond at the Loch Ness Centre to be viewed by unsuspecting visitors. Some thought it was a shark, and others, a crocodile, which is reminiscent of the sighting mentioned above. However, the list of suggested real animal candidates is a long one:

1. Giant eel
2. Giant squid
3. Giant pinniped (Oudemans)
4. Long-necked seal
5. Long-necked newt
6. Plesiosaur (Dinsdale)
7. Great sea serpent (Gould)
8. Hypothetical form of vastly enlarged long-necked newt (Gould)
9. Hypothetical type of long-necked seal
10. Animal whose identity remains to be established
11. Animal belonging to a known species (e.g., sea lion) not recognized by observer
12. Animal belonging to a species thought to be extinct
13. Marine creature trapped and evolved from a plesiosaur
14. Sturgeon (Adrian Shine)

How did the animal(s) get into the loch

There are two possibilities. They either have been trapped in the loch for thousands of years or have entered recently perhaps within the last 100 years or so.

Some speculate that at the end of the ice age 10,000 years ago, the ice melted and the sea was raised and flooded the land along inland valleys, and Loch Ness was linked to the sea. The animals swam into the loch but found their return route closed because the land rose, and Loch Ness became an enclosed lake eventually, losing its salinity and becoming freshwater. The other possibility is the River Ness flowing into the sea at Inverness, but the river is probably too shallow to permit the passage of very large animals. The fact that the loch is now some 16 m above sea level rules out the possibility of a tunnel. It should also be noted that the Caledonian Canal has locks at both ends and throughout its length.

The question is still what are they: reptile, amphibian, mollusk, fish, or something that does not fit into any of these types.

The most widely thought is that it is a plesiosaur – a marine fish-eating reptile contemporary with the dinosaurs and thought to have been extinct for 70 million years. This theory was put forward by Dr. Denys Tucker, former British Museum expert. If correct, it would be the greatest zoological find for centuries, and indeed, *Elasmosaurus* of the plesiosaur family is known to have existed in the British Isles.

It seems incredible that the research to date has been carried out on a shoestring budget, though interest has been shown by the British Natural History Museum, Smithsonian Institution, BBC, Freshwater Biological Association, NASA,



Lake Monster, Figure 4 View from Urquhart Castle, Loch Ness showing a flotilla of 24 motor launches equipped with Lawrence echo sounders; some 1,500 h sonar patrols were made, patrolling the loch over a period of a week.

Eastman Kodak, MIT, Academy of Applied Science, and many others, including many universities in Europe and the United States.

Over a thousand people have contributed to the Loch Ness work in one way or another. Many are volunteers to the Loch Ness Investigation and the Loch Ness Project. A list of those completing university dissertations for university degrees may be found on www.lochnessproject.com.

I hope it's there. But I hope they don't find it-because if they do, they'll do something nasty to it.

Dr. David Bellamy, 1991

I am not yet certain of the ending, but in the course of a decade I have watched the plot develop, and an almost empty stage slowly fill with characters – each with a part to play, a contribution to make, however small – to the whole tremendous story.

Tim Dinsdale, 1976

If monsters exist, then science, a mainstay of our conventional wisdom, has ignored the most exciting wildlife mystery in the British Isles; if there are none, then over one thousand people including doctors, clergymen, M.P.s, civic dignitaries and a saint may have lied; unthinkable. Alternatively, they were sincerely and unshakably mistaken; even more worrying!

Adrian Shine, 2006, The Loch Ness Project

It looks as if the existence of a population of very large animals in Loch Ness is about to be finally confirmed.

Sir Peter Scott, 1975 (Review)

Acknowledgments

Acknowledgment is made to Taylor and Francis Books UK for permission to reproduce [Figure 1](#) and [3](#) from

“The Loch Ness Monster” by Tim Dinsdale First Edition 1961 (pages 74, 84) and Third Edition 1976 (photo No. 8), Routledge & Kegan Paul London and Boston; and [Figure 4](#) from Loch Ness 2006, Adrian Shine, The Loch Ness Project.

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Cross-references

Bathymetrical Survey of the Scottish Freshwater Lochs, 1897–1909

Lough Neagh

LAKE OUTBURSTS

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Introduction

Glacial lake outbursts have always fascinated scientists but also concerned populations living near glaciers, just as they worry populations living downstream of dams built by humans. Such outbursts have frequently caused catastrophes resulting in the complete destruction of villages and the deaths of hundreds of people. In terms of geomorphology, over the past several decades, quaternary scientists have sought to document the effects of recent and past glacial outbursts to reconstruct the deglaciation history of areas where they prevailed and to show how powerful the outbursts are.

The first goal of this paper is to point out the recent implementation of monitoring networks for glacial dams and glaciers in several parts of the world, with regard to the risk of glacial outbursts.

The second is to bring together and describe the typical features of glaciofluvial landforms partly or entirely created by glacial outbursts resulting from the sudden drainage of glacial lakes and to identify their settings. These features are defined on the basis of the specific characteristics of fluvial corridors, that is, erosional and depositional forms, the characteristics of sediments and their stratigraphic position. This document provides the most up-to-date list of the typical geomorphological features of surfaces reshaped by glacial outbursts (Robitaille and Dubois, 1995; Robitaille, 1989). Throughout the world, in the view of Hugget (1994), Robitaille and Dubois (1995), Robitaille (1989), and several others, various unexplained landforms on the earth's surface are probably the result of catastrophic floods. In fact, as stated by Tricart and Cailleux (1962), generally speaking, it is possible that the role of glacial outbursts has too often been overlooked in the study of glaciofluvial environments. Glacial outbursts, because of their magnitude, first result in spectacular erosion upstream and then displace huge quantities of material that are deposited downstream. Areas of erosion and sedimentation follow

each other, mainly depending on slope variations; major modifications of the streambed and its immediate environment therefore ensue.

Despite the high number of glacial dam breaches that have occurred throughout the centuries, there are relatively few studies concerning the geomorphological consequences of glacial outbursts at inland margins (Table 1) and from alpine and northern glaciers (Table 2).

Monitoring glacial lakes

The occurrence of glacial outbursts and, chiefly, their impact on infrastructure and human lives have been preoccupying populations for centuries. In the Little Ice Age, numerous readvances of alpine glaciers led to breaches in morainic dams, triggering sometimes deadly outbursts. Today, in the context of global warming and with the assistance of increasingly sophisticated tools, the governments of many countries have set up monitoring networks (United Nations, 2002). Accordingly, the behavior of hundreds of glacial lakes has been monitored, sometimes for several decades, for example, in Alaska or in the Canadian or American Rockies (Devaris, 2006; US Geological Survey, 2002), in the Himalayas (Government of Nepal, 2006; United Nations, 2002) or in Iceland (Hardardottir et al., 2005). Monitoring networks, sometimes manned by volunteers, have even been created in the Himalayas and in Iceland, for instance (World Volunteer Web, 2006; UNEP, 2000).

Terminology of lake outbursts

In the literature, several terms have been used to identify the entire phenomenon or its consequences. English speakers use the terms *glacier burst*, *glacier outburst*, *glacial outburst*, *glacier flood*, and *debris flow*. The materials accumulated when glacial lakes are drained are known as *glacier outburst deposits* or *accumulations en nappe de débâcle glaciaire* in French (Robitaille and Dubois, 1995) and differ from *outwash deposits* and *ice-contact deposits*. Since Rabot's work (1905), the term *débâcle glaciaire* has been used by French Europeans to identify the sudden and violent discharge of water from a glacial lake (proglacial and sub-, en-, and supraglacial pockets of water). It therefore means a catastrophic glaciofluvial flood. For French speakers, the term *debacle* is usually associated with a drift ice phenomenon, that is, with flooding in rivers and streams resulting from spring runoff (Georges, 1970), but Baulig (1970), Michel and Fairbridge (1980), and Étongué Mayer et al. (2002) clearly distinguish it from *débâcle glaciaire* or *glacial outburst*.

Glacial outbursts are also known by other names. For example, in Iceland and other countries, the term *jökulhlaup* denotes the violent discharge of sub-, en- and supraglacial pockets of water resulting from subglacial volcanic eruptions (Thorarinsson, 1956; Gomez et al., 2000; Magilligan et al. 2002). In Peru, because they transport huge amounts of sediments, they are known as *alluvione* or *huayco* (Tufnell, 1984).

Lake Outbursts, Table 1 Geomorphological consequences: mega glacial outbursts

Geomorphology of the fluvial corridor						
Author	Place	Type of dam	Depositional forms			Stratigraphic position
			Erosion forms	Forms	Characteristics of sediments	
Pardee, 1910, 1942; Bretz, 1923a, 1923b, 1928, 1929, 1932, 1959, 1969; Bretz et al., 1956; Baker, 1973, 1978; Baker et al., 1987; Burns and Cordero, 1993	Washington State and Oregon (USA)	Ice	Deep channels in bedrock Braided channels in bedrock Cataracts Rock walls Giant kettles Grooves Pool and riffle fluvial profile Scouring of till surfaces	Deltas Sandur Giant current ripples Block fields with or without matrix Braided channels Pendant bars Eddy bars Expansion bars	Layered sand, gravel, and pebbles Unsorted deposits Huge bars of fluvial sediments Mostly coarse-grained particles, poorly sorted deposits Particles of all sizes, unsorted deposits Sheets of fine sediments (turbidites) Unsorted deposits	Sand and gravel over till
Gilbert, 1890; Stearns, 1936; Malde, 1968; Frödin, 1954; Skinner, 1973; Smith and Fisher, 1993; Graham and Teller, 1984; Dubois, 1979	Idaho (USA), Canada and Scandinavia	Unknown	Deep channels in bedrock (basalt) Marginal channels Cataracts Rock walls Widening of valley	Huge bars of “melon gravel” Sand sheets Fine sedimentation (temporary lakes along the corridor) Very thick block fields Outwash Deltas Terraces Fluvial bars Pendant bars Alcove bars		
Kehew, 1982, 1990, 1993; Kehew and Clayton, 1983; Kehew and Lord, 1986; Lord and Kehew, 1987; Lord, 1991; Kehew et al., 1989; Kehew and Teller, 1994; Catto et al., 1982; Teller, 1988; Teller and Thorleifson, 1983, 1987	Saskatchewan and Manitoba (Canada), North Dakota, Michigan, Mississippi basin (USA)	Unknown	Deep channels in till Terraces carved in till Scarps Channels in till of floor of lacustrine basin upstream of dams Braided channels in till Channels in till Bars and islets of unaffected residual till		Unsorted deposits Well-sorted and well-layered sand and gravel Unsorted sand and gravel with angular blocks	

Lake Outbursts, Table 2 Geomorphological consequences: glacial outbursts in Alpine and Northern Regions

Geomorphology of the fluvial corridor						
Depositional forms						
Author	Place	Type of dam	Erosion forms	Forms	Characteristics of sediments	Stratigraphic position
Agassiz, 1840	Switzerland	Ice and moraine	Deep channels Scarps			
Rabot, 1905	Alpine and northern regions	Ice and moraine	Deep channels in till	Block fields Sheets of gravel and stone	Angular to subangular particles Unsorted coarse-grained deposits	
Kerr, 1934, 1936	British Columbia (Canada)	Ice and moraine	Channels in outwash	Block fields Sheets of coarse-grained pebbly sediment	Rounded to subrounded particles Unsorted deposits	Poorly sorted coarse-grained deposits over glaciofluvial deposits
Aitkenhead, 1960	Norway	Ice	Widening of streambed			
Mathews, 1965	British Columbia (Canada)	Ice	Widening of streambed			
Noff, 1966	Oregon (USA)	Moraine	Channels in till Breaches in frontal moraine	Block fields Sheets of fine subaqueous sediments	Angular to subangular particles	
Richardson, 1968	Washington (USA)	Ice and moraine	Scarps Shallow channels Terraces carved in till	Block fields	Angular to subangular particles	
Maag, 1969	Axcel Herberg Island (Canada)	Ice	Scarps Channels in outwash and till	Sheets of pebbles and blocks	Unsorted deposits	
Fahnestock et al., 1969	Alaska (USA)	Ice	Channels in outwash Scarps	Alluvial dunes Sheets of pebbles and blocks		Recent alluvial dunes over old alluvial dunes
Post and Mayo, 1971	Alaska (USA)	Ice	Deep channels Scarps	Giant current ripples Thick sheets of pebbles and blocks	Unsorted deposits	

Bradley et al., 1972	Alaska (USA)	Ice	Channels in outwash Scarps	Alluvial dunes Block fields	Poorly sorted and unsorted deposits
Vivian, 1974	Western Alps	Ice and moraine	Widening and deepening of streambed Deep channels Scarps	Sheets of coarse-grained sediments	
Lliboutry et al., 1977	Peru	Moraine	Channels in till and outwash	Coarse-grained alluvial fans Block fields	Unsorted coarse- grained deposits Angular to subangular particles
Theakstone, 1978	Norway	Ice	Breaches in frontal moraine Deep channels Scarps	Sheets of pebbly debris Sheets of silty debris Block fields	
Yesenov and Degovets, 1979	USSR	Ice	Deep channels	Accumulation of enormous blocks	
Jackson, 1979	British Columbia (Canada)	Ice	Deep channels in till	Sheets of gravel Coarse-grained alluvial fans	Unsorted coarse- grained deposits
Young, 1980	Alaska (USA) Yukon (Canada)	Ice	Deep channels Slides in lacustrine basin	Giant current ripples	Recent alluvial fans over old alluvial fans
Xu, 1981	Tibet	Moraine	Breaches in frontal moraine Widening of streambed	Sheets of pebbles and gravel Block levees Block levees with sandy matrix Sandy terraces on convex banks	Unsorted deposits Coarse-grained particles (blocks on the surface)
Yanamaka, 1982	Nepal	Ice and moraine	Deep channels	Sheets of pebbles and gravel Terraces	Unsorted angular particles Unsorted deposits
Beecroft, 1983 Hewitt, 1964, 1982; Qinghua, 1991	Switzerland Himalayas (Central Asia)	Ice Ice	Channels in outwash Widening and deepening of streambed Deep channels Scarps Slides on scarps	Sheets of gravel Sheets of coarse-grained deposits and kettle formation	Unsorted deposits

Lake Outbursts, Table 2 (Continued)

Geomorphology of the fluvial corridor					
Author	Place	Type of dam	Erosion forms	Depositional forms	
				Forms	Characteristics of sediments
Haeberli, 1983	Switzerland	Ice Moraine	Channels in till	Till-derived block fields	Unsorted deposits Angular to subangular particles
Clague et al., 1985	British Columbia (Canada)		Deepening of streambed Erosional scarp Slides on scarps Channels in till	Coarse-grained alluvial fans Sheets of pebbly debris	
Blown and Church, 1985	British Columbia (Canada)	Moraine	Channels in till	Coarse-grained alluvial fans containing blocks	Unsorted deposits
Fushimi et al., 1985	Nepal	Moraine and ice	Terraces carved in till	Giant current ripples Coarse-grained alluvial fans Sheets of coarse-grained deposits and kettle formation	Unsorted deposits Unsorted deposits Unsorted deposits
Clague, 1975, 1987	British Columbia (Canada)	Moraine	Deep channels Breaches in frontal moraine		
Magilligan et al. 2002;	Iceland	Ice	Terraces carved in till Deep channels Channels in glaciofluvial terraces	Sheets of coarse-grained gravel containing blocks Block fields	Unsorted deposits Unsorted deposits
Hardardottir et al. 2003 2005;	Nepal	Moraine	Channels in till Erosional terraces		
Maizels, 1997			Slides on scarps	Poorly sorted gravel sheets over glaciofluvial deposits	Poorly sorted gravel sheets over glaciofluvial deposits
Vuichard and Zimmerman, 1986, 1987	Norway	Ice	Channels in glaciofluvial terraces Breaches in frontal moraine		
McCarrol and Matthews, 1989			Grooves in bedrock	Block fields	

However, *lake outburst* could be a general term that would include both glacial lake outbursts and those of reservoirs.

Glacial outbursts

There is little reference documents dealing with the geomorphological role of glacial outbursts. However, authors discussing them always highlight their great erosional power and transport capacity. Glacial outbursts are considered events of major, if not catastrophic, importance in fashioning proglacial environments – events that can transport hundreds of thousands of cubic meters of material (Tricart and Cailleux, 1962; Price, 1973; Embleton and King, 1975).

Glacial outbursts are divided into two categories based on their environment: mega outbursts at inlandis margins and outbursts in alpine and northern regions.

Mega glacial outbursts at inlandis margins

The best-known studies of long-ago mega glacial outbursts at the leading edge of inlandis are those concerning large glacial lakes Missoula (Spokane Flood), Bonneville (Bonneville Flood), Regina, and Souris, all located in the center and west of North America, as well as Lake Agassiz, in the east. The large jökulhaups that occur in Iceland can also be included.

In every case, the estimated flows have involved hundreds of thousands of cubic meters per second, and the resulting geomorphological transformations have been varied, significant, and most often erosion related (Dawson, 1992). Most of the landforms are hundreds of square meters or more in size (Figure 1). The deep channels and bars of sediments, for example, have been used as models in interpreting large-scale erosional and fluvial

sedimentation landforms on Mars (Baker and Milton, 1974; Rice, 2006). Table 1 presents the main geomorphological characteristics of the landforms shaped by these mega glacial outbursts. They are mainly deltas, giant current ripples, braided channels incised into the bedrock (basalt), block fields derived from till, large quantities of unsorted sediments, erosion notches, abandoned cataracts, giant kettles, large-scale abandoned dendritic drainage networks, etc. This landscape remodeling may have affected territory over a distance of up to 1,000 km in the case of the outburst of Glacial Lake Missoula in the United States (Ice Age National Scientific Reserve, 2007).

Glacial outbursts in alpine and northern regions

There are many detailed studies specifically pertaining to fluvial corridors remodeled by recent glacial outbursts in alpine and northern regions (Table 2). These glacial outbursts are smaller than those previously mentioned. They involve glacial reservoirs behind dams up to 150 m high (Government of Nepal, 2006), generally containing several million cubic meters of water but sometimes as much as 90–100 million cubic meters (Government of Nepal, 2006), with flow in the order of 500–5,000 m³/s, but that can reach 300,000 m³/s (Hardardottir et al., 2003). Therefore, although the geomorphological transformations may be less varied and less impressive than is the case at inlandis margins, they are nonetheless significant. Moreover, in several cases, the outbursts even occur annually (Hardardottir et al., 2003).

Nevertheless, the power of the water during these glacial outbursts is amazing. In the cases reported, the authors always highlight their great geomorphological effectiveness and their power compared to all other types of glaciofluvial flow (Vivian, 1974). The displacement of



Lake Outbursts, Figure 1 Dry falls. The falls were created following the catastrophic collapse of the ice-dam of “Glacial Lake Missoula.” (Photo: A. Robitaille.)



Lake Outbursts, Figure 2 Breach in till caused by the outburst of an artificial dam (*right* of the photo), lac Beloeil, Québec, Canada. (Photo: A. Robitaille.)

a volume in the order of 4.9 million metric tons has even been reported for a single event (Hardardottir et al., 2005), even reaching 40 million in some cases (US Geological Survey, 2002). A summary of the work on this type of glacial outburst brings to light many geomorphological characteristics related to erosional and depositional processes.

Although there are not many erosion forms, they can be observed in the majority of remodeled fluvial corridors. The main forms noted are deep channels in scarps, erosion terraces carved in till, breached frontal moraines, and landslide scars in scarps. Depositional forms are more varied. Moreover, some of their sedimentary characteristics (e.g., poor sorting, barely discernible structure) are specific to glacial outbursts. The most frequently observed forms are block fields derived from till, outburst deposits, current ripples, coarse-grained alluvial fans, boulder bars, and terraces covered with coarse-grained material, as well as sand spits containing antidunes.

Classification of the typical features of lake outbursts

Analysis of past cases of glacial outbursts, as well as of an outburst at an artificial lake studied in the field (Figure 2) in Québec (Robitaille, 1993; Robitaille and Dubois, 1989), identified seven general characteristics (Table 3). They can be used to reconstruct the events related to glacial outbursts, facilitate the interpretation of specific or complex proglacial environments, and pinpoint where glacial outbursts occurred in formerly glaciated areas. Glacial outbursts may have partly or completely remodeled glaciofluvial landforms and even transformed a glacial environment consisting of till into glaciofluvial landforms.

Dry glaciolacustrine basins

In the case of a proglacial lake, typical forms of dry glaciolacustrine basins are mainly concentrated immediately upstream of the lake's spillway. They consist mainly of wide shallow landslide scars cut into the floor of the lacustrine basin. However, in the absence of both small scarps marking the boundary of the landslide niche and of residual mounds consisting of glaciolacustrine deposits or till, the scars are not very visible in the field. The second characteristic landform is an erosion notch extending into the axis of the spillway, petering out towards the interior of the basin. The notch is generally lined with blocks and bordered by a scarp. Elsewhere in the dry basin, other features contribute to the identification of a glacial outburst: the absence of a strandline below the lower limit of the scouring, the presence of varved glaciolacustrine sediments not overlain by fill material such as sand and gravel. Abandoned dendritic drainage networks mark the sediments of the dry basin's floor.

Breached morainic dams

In the case of a moraine-dammed lake, when the dam consisting of till or glaciofluvial deposits is breached and the lake is drained, a deep channel (spillway) is formed. In the absence of a bedrock, the channel reaches the lower levels of the lacustrine basin, extending onto its floor. Its scarp slopes gently due to colluviation of the unconsolidated material, and it is lined with blocks, which are sometimes quite large, from scouring of the surrounding material. This debris rests on till or bedrock.

A depositional landform is almost always associated with the breach. Immediately downstream of the moraine, an alluvial fan forms a slightly rounded cone. In the axis of

Lake Outbursts, Table 3 Typical features of glaciofluvial landforms resulting from glacial outbursts

Geomorphology	Associated forms and sediments
Dry glaciolacustrine basin	Slide scars and gullies Channels in basin floor Till-derived block fields Erosional scarp Abandoned dendritic drainage network
Breached morainic dam	Breached frontal moraine Deep channels Erosional scarp Coarse-grained alluvial fans Till-derived block fields
Erosion notches	Erosional scarp Till-derived block fields Slide scars and gullies on scarps and slopes Boulder bars or block levees Block fields (depositional) Coarse-grained alluvial fans
Outburst deposit	Continuous terraces or terraces remnants Erosional scarp Rectilinear or braided channels Giant current ripples Kettles Frontal scarps Sand spits Streamlined and rounded mounds
Erosional terrace	Rectilinear or braided channels Erosional scarp Till-derived block fields
Fine sediment bars and islets	Deltas Braided channels Streamlined and rounded mounds
Erosion forms in bedrock	Channels Cataracts Giant kettles Grooves

the breach, it can be eroded by subsequent fluvial action. However, its distal portions are well preserved. This alluvial fan consists of coarse-grained angular to subrounded sediments, depending on the nature of the materials composing the floor of the lacustrine basin and the dam. These materials have no sedimentary structure since they are very rapidly deposited in a mixture of water, mud, and debris of all sizes. However, they can display layering and very distinct graded bedding (from blocks to sand over a span of 200–300 m) and overlie a variety of unconsolidated formations (till, glaciofluvial deposits, etc.).

Erosion notches

Erosion notches in unconsolidated materials, occurring successively from upstream to downstream in sections with steeper slopes, are characteristic of glaciofluvial landforms resulting from glacial outbursts. They are evidence of the erosional power of glacial outbursts and

that their magnitude significantly exceeds the competence of fluvial systems. These erosion notches are very variable in length and width and form rectilinear or slightly curved corridors. They are deeper and narrower in steeply sloping sections and shallower and wider on gentler slopes. In some sections, all unconsolidated material has been totally washed away down to the bedrock, which can even be marked by grooves caused by the displacement of large blocks.

Most of the time, where the notches occur, glaciofluvial accumulations are swept away and erosion reaches the underlying till. The notches are bordered by the now sloping scarps, resulting from colluviation of unconsolidated material. The floors of the notches are planar and lined with coarse-grained material, forming till-derived block fields, which are usually matrix free. Presumably, however, various sources of sediments, due to colluviation of notch scarps or to subsequent fluvial action, could produce considerable inflows of finer material in certain areas of these block fields.

Other forms, frequently associated with these notches, can also be identified: landslide scars or gullies in the scarps, depositional block fields and boulder bars.

In sections where erosion notches incise thick unconsolidated formations, the scarps display many slide scars. The same is true in the narrow sections of valleys, where slides and gullies occur. In both cases, they form rectilinear scarps perpendicular to flow. They are very variable in size and shape and never have accumulation rims at the base, since the debris is carried away by the waters of the glacial outburst.

Immediately downstream of the erosion notches, specifically at knickpoints, blocks from upstream blanket the surface. These blocks are included in a matrix of fine sediments, also from upstream, and overlie various unconsolidated formations or the bedrock.

Block levees, consisting of piles of blocks, occur downstream of the erosion notches at the top of the scarps. They form long crests, variable in height and width.

Glacial outburst deposits

Glacial outburst deposits and the forms associated with them represent, with erosion notches, one of the main characteristics of glaciofluvial landforms resulting from glacial outbursts. They are evidence of rapid emplacement in a very high-energy fluvial environment, corresponding to the outburst's flood wave. They are mainly distinguished by the nature and arrangement of the sediments composing them. The sediments come from eroded surfaces upstream, including moraines, glaciofluvial deposits, and other unconsolidated formations. In general, they are coarse grained and contain a small percentage of particles less than 2 mm in diameter (Figure 3). They have no apparent sedimentary structure and are very poorly sorted. On the other hand, the sediments can be sandy and have large-scale cross-bedding. These accumulations usually cover large areas, blanketing various unconsolidated formations, and range from a few dozen centimeters to several meters in thickness.



Lake Outbursts, Figure 3 Typical glacial outburst deposits in Laurentian Hills, Québec. (Photo: A. Robitaille.)

The outburst deposits are emplaced in flat to gently sloping sections of the fluvial corridors and totally blanket the surface. In general, from the outset of the lake's drainage phase following the outburst flood wave, they are carved in such a way that they form terraces. Seen from above, these accumulations have several characteristics specific to outwash, such as relatively planar topography sprinkled with kettles, terraces, and rectilinear or braided channels (Figure 4). They also have multiple marks of subsequent fluvial erosion (meanders, scarps, etc.). However, their surface shows depositional forms usually associated with glacial outbursts: frontal scarps, sand spits, and current ripples.

The frontal scarps abruptly delineate the downstream extremity of the outburst deposits. They are oriented perpendicular to the direction of flow and have a sinuous, gently sloping front, whose height is comparable to the thickness of the deposits.

The sand spits occur downstream of large blocks or other obstacles to the flow. They vary in length and thickness, depending on the size of the obstacle. They are streamlined and can include sedimentary structures reflecting high fluvial energy, such as antidunes.

The giant current ripples consist of a succession of asymmetric mounds, comparable to the smaller ones commonly observed on streambeds. They vary considerably in size and composition, depending on the power of the outburst. They can be up to a few meters high and several dozen meters apart. They generally consist of poorly sorted sand and gravel.

Erosion terraces

Erosion terraces are formed on the initially convex and sheltered banks of the fluvial corridors. The outburst flood wave scours the surface first, and then the water draining



Lake Outbursts, Figure 4 Braided channels on the Markarfljot River after the 2010 Eyjafallajökull eruption, Iceland. (Photo: A. Robitaille.)

from the lake carves deep channels into a portion of the surface. Their topography is planar, sprinkled with flood-scoured blocks, and displays several characteristic forms such as rectilinear or braided channels. The former are generally short and shallow and are sometimes filled with poorly sorted sand and gravel. The latter wind through the many bars and islets carved into the till.

Fine-sediment bars and islets

Bars and islets composed of fine sediment (sand, gravel) usually occur in the distal portion of the fluvial corridor, where the water's transport capacity is considerably reduced. The sediment can be deposited in a lake or on

a very large flat surface along the fluvial corridor, but is generally deposited near the mouth. This type of sedimentation can lead to the formation of deltas or can cover marine sediments.

Fine-sediment bars and islets usually consist of sand and gravel. They are poorly sorted, but may display some layering. Their sedimentation environment is subaqueous or subaerial. Seen from above, they form a field of bars and islets intersected by braided channels. These fluvial forms are streamlined in the direction of flow and have rounded centers.

Erosion forms in bedrock

Erosion forms in bedrock result from very powerful erosional agents, such as those related to mega glacial outbursts, and affect bedrock surfaces that are not very massive and relatively brittle. The forms consist mostly of cataracts, deep channels, giant kettles, and grooves.

Conclusion

Several catastrophes in the past few centuries have prompted governments and international organizations to set up monitoring networks. In the context of global warming, which is liable to increase the number and frequency of glacial outbursts, the methods used to monitor the behavior of glacial lakes and glaciers have been refined, and it seems to be increasingly appropriate to study the effects of glacial outbursts along inhabited or developed fluvial corridors.

The geomorphological impacts of glacial outbursts highlight their great erosional power and transport capacity. They are capable of transforming and remodeling some or all materials located in the fluvial corridors over very great distances. The compilation of studies relating to glacial outbursts all over the world and the detailed study of the geomorphological impacts of the breaching of artificial dams have made it possible to identify the characteristic features of typical glaciofluvial landforms. This has led to the classification of erosional and depositional forms associated with mega outbursts, which shaped huge territories at inland margins in the past, and with outbursts that still occur today in alpine and northern regions. A landform with a particular pattern cannot only be used to reconstruct past events associated with glacial outbursts but also to try to predict the geomorphological impacts of future outbursts.

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Cross-references

[Dam Failures: Impact on Reservoir Safety Legislation in Great Britain](#)
[Glacier Jökulhlaup Hazards](#)
[Large Dams and Environment](#)

LAKE RESTORATION

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Definition

Lake restoration is a broad term used for different techniques aiming to bring a lake back to or closer to anthropogenically undisturbed conditions. Usually, lake restoration refers to methods used *inside* the lake, but sometimes it also refers to measures taken *outside* the lake such as reduction of the external nutrient loading by improved waste water treatment.

Introduction

The vast majority of lake restoration projects have been conducted to combat eutrophication. However, lake restoration has also been used in other contexts, for instance to counteract acidification in soft water lakes (a topic not included here). Eutrophication of lakes due to high nutrient loading (especially phosphorus) has been the paramount environmental problem for lakes worldwide for the past approximately 50 years (Carpenter et al., 1999).

Lake Restoration, Table 1 Most commonly used lake restoration methods to overcome eutrophication

Methods	Main principles and <i>possible problems</i>	References
<i>Physical methods</i>		
Sediment dredging	Phosphorus rich sediment is removed to reduce the internal loading of phosphorus. <i>Relatively expensive method. Disposal sites needed</i>	Van der Does et al. (1992); Annadotter et al. (1999)
Dilution/flushing	The lake is flushed with nutrient poor water to decrease phosphorus concentrations in the lake water. <i>Depends on the availability of large amounts of nutrient poor water</i>	Jagtman et al. (1992); Welch and Patmont (1980)
Water level manipulation	Increased water level decreases the risk of resuspension of sediment in shallow lakes. Decreased water level increases the growth potential of submerged macrophytes. <i>Not always easy to manipulate water level or to get permission to do so</i>	Chow-Fraser (2005); Blindow et al. (1993)
Hypolimnetic withdrawal	To increase the outflow of phosphorus, the lake water outflow is redirected through a pipe to the hypolimnion where phosphorus accumulates during summer stratification in deep lakes. <i>The outlet of nutrient rich and may be anoxic water may create problems for downstream water bodies</i>	McDonald et al. (2004); Nürnberg (2007)
Macrophyte harvest	Nuisance growth of macrophytes is removed to improve conditions for boating and fishing. <i>If growth conditions are favorable, the macrophytes will soon return</i>	Pieterse and Murphy (1990); Olson et al. (1998)
<i>Chemical methods</i>		
Hypolimnetic oxygenation	Oxygen (or air) is led to the hypolimnion of deep lakes to increase redox conditions and sorption of phosphorus. <i>Long-term treatment (>10 years) is often needed and, still, permanent effects are difficult to obtain</i>	Gächter and Wehrli (1998); Liboriussen et al. (2009)
Phosphorus inactivation	Salts of aluminum, iron, calcium, or other phosphorus-binding agents are added to the water and/or the sediment to decrease the internal loading of phosphorus. <i>Aluminum is toxic at low and high pH which makes it difficult to use in soft water lakes or in lakes with high pH</i>	Welch and Cooke (1999); de Vicente et al. (2008)
Nitrate addition	Nitrate is added to the sediment to oxidize the organic matter, decrease the future oxygen demand, and increase phosphorus sorption. <i>Nitrate addition is problematic in nitrogen-limited lakes</i>	Ripl (1976); Søndergaard et al. (2000)
<i>Biological methods</i>		
Removal of zooplankton-eating fish	Zooplankton- and/or benthic invertebrate-eating fish are removed to increase the number of large zooplankton and their grazing on phytoplankton. <i>Permanent effects may be difficult to obtain</i>	McQueen (1998); Søndergaard et al. (2008)
Stocking of predatory fish	Fish-eating fish are added to decrease the number of zooplankton-eating fish and improve zooplankton numbers and phytoplankton grazing. <i>Correct timing of stocking is crucial to achieve effects</i>	Benndorf (1995); Skov and Nilsson (2007)
Stocking with herbivorous fish	Plant-eating fish (grass carps) are added to reduce excessive growth of submerged macrophytes. <i>Phytoplankton takes over instead of macrophytes and creates turbid water</i>	Hanlon et al. (2000); Shireman and Maceina (1981)
Macrophyte transplantation and protection	Submerged macrophytes are established and protected from plant-eating birds or fish to maintain high macrophyte coverage. <i>Relatively large areas of protected macrophytes are needed</i>	Lauridsen et al. (2003); Qiu et al. (2001)
Introduction of mussels	Mussels are introduced to increase the filtration of the water and create clearer water. <i>Often zebra mussels (<i>Dreissena polymorpha</i>) are used, but this species is also invasive and may reach very high densities with negative biological and physical consequences</i>	Roy et al. (2010); Gulati et al. (2008)

Eutrophication has led to turbid water, blooms of (often toxic) cyanobacteria, loss of biodiversity, and many other changes in biological structure and functioning (Jeppesen et al., 2000). During the past decades measures have been taken in many parts of the world to reduce external nutrient loading via improved waste water treatment or diversion of nutrient rich inlets. However, particularly in developing countries nutrient loading is still increasing and the worst problems may not yet have occurred (Le et al., 2010).

Furthermore, even after a reduction of the external phosphorus loading the effects obtained may be unsatisfactory. This may reflect that the external nutrient loading

reduction has been insufficient with the result that phytoplankton is not adequately limited by nutrients. However, the lack of success may also be due to chemical or biological resistance factors inside the lake preventing or delaying improvements. Chemical resistance is caused by the release of phosphorus from a pool accumulated in the sediment when loading was high. Depending on the loading history and release mechanisms, this internal phosphorus loading typically persists for 10–15 years after the loading reduction until new equilibrium conditions are established (Jeppesen et al., 2005). Biological resistance can emerge through several biological elements which do not respond immediately to reduced loading, the

main factors are: (1) the fish community, which at increasing nutrient concentrations increases in numbers and becomes dominated by bottom-feeding species which resuspend sediment and create turbid water in their search for food, and zooplankton-eating fish species which establish a high predation pressure on zooplankton, implying that zooplankton control of phytoplankton is low; and (2) the submerged macrophytes, which at increasing nutrient loading and enhanced turbidity disappear or become strongly reduced in abundance in shallow lakes, but often show a delayed recolonization after a loading reduction. In shallow lakes submerged macrophytes are important for maintaining stable clear water conditions (Scheffer et al., 1993).

Lake restoration methods

A number of different methods to restore lakes by combating eutrophication have been investigated throughout the world for the past 20–30 years (Moss et al., 1996; Perrow and Davy, 2002; Cooke et al., 2005). Basically they can be divided into two types: (1) physical and chemical methods which aim to reduce phosphorus availability, that is, reduce the phytoplankton biomass by nutrient limitation (bottom up control) and (2) biological methods which change the biological control of the phytoplankton, for example through increased zooplankton grazing (top down control). Table 1 gives an overview of the most commonly used lake restoration methods, the principles behind, potential problems, and selected references for further information.

Results, recommendations, and future challenges

So far, most experience with lake restoration is established for northern temperate regions, although in recent years lake restoration has attracted increasing attention also in warm countries. Generally, most reported restoration initiatives have led to improvement, sometimes only in limited parts of the ecosystem, however, and the longevity of the improvements varies from a few months to more than 10 years. Only few restoration projects exist that document effects for more than a few years following the intervention.

An important prerequisite for successful restoration is prior knowledge of the lake and its catchment before planning and conducting the intervention. In particular, focus should be directed at external nutrient loading. If this is too high then long-lasting effects of restoration cannot be expected and the lake will sooner or later return to pre-intervention conditions. For shallow lakes phosphorus equilibrium concentrations below 0.05–0.1 mg P/l have been suggested, and in deeper lakes even lower concentrations are required (Jeppesen and Sammalakorpi, 2002).

In the future, lake restorations may become even more relevant because of increased demand for clean drinking water and because increased nutrient loading can be anticipated from farming areas that increase in area, due to human population growth, and expectedly will be cultivated more intensively. In developing countries enhanced

use of fertilizers and introduction of sewage systems may increase the nutrient loading. Climate changes may affect both temperatures and precipitation patterns throughout the world leading to a reinforcement of eutrophication and risk of toxic algal blooming, and the demand for successful lake restoration techniques will therefore grow (Jeppesen et al., 2009a, b).

Summary

Lake restoration can be a powerful tool to improve lake water quality, but successful restoration and lake recovery depend on a sufficient reduction of the external nutrient loading combined with sufficient restoration action. The most commonly used methods include addition of phosphorus sorption agents such as aluminum and biological methods such as removal of zooplankton-eating fish. New and improved lake restoration methods are developed and tested continuously.

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[Urban Lakes and Ponds](#)

LAKE SEDIMENTS

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Introduction

Lakes receive a wide assortment of suspended materials from rivers, precipitation, catchment erosion, shoreline erosion, pollution sources, and biological activities. These materials are referred to as sediments and are a very important factor in the life of a lake or reservoir. The material tends to fill lakes and reservoirs thereby restricting their intended use and, in the worst scenario, eventually converting them into marshlands or swamps.

In the case of reservoirs used for water supply, sediment may reduce the reservoir capacity to such an extent as to threaten the very existence of the reservoir which may become full and consequently unserviceable.

Organic, glacial, and volcanic sediments

Sediments vary according to the origin of the lakes. Glacial or glacial-type lakes receive many different

materials from rivers and shores which range from large boulders, rocks, pebbles, and coarse sands to fine sands, silts, and clays. In addition, organic debris resulting from eutrophic processes in the lake settles to the bottom and mingles with the inorganic sediments.

Lakes of volcanic origin are normally more rocky than glacial type lakes and contain only limited quantities of fine silt material. Volcanic ash is generally more prevalent in the bottom sediments of volcanic lakes and is useful in determining the age of the lake.

Opportunity is taken for the deposition of sediment to be studied and measured. If such measurements are carried out at appropriate intervals of time, total sediment load can be estimated.

Knowledge of reservoir sedimentation and its control remains limited although significant progress has been made. The study of lake and reservoir sediment control requires to be based on reliable field data or for the verification of physical and mathematical modeling.

As lakes become more eutrophic, organic deposition increases and the content of sediments increases promoting vegetation growth. This has the effect, in turn, of adding more organic material to the sediments and hastening the death of the lake. Oxygen demand also increases with increased organic sedimentation.

Reservoirs may contain substantial amounts of humus, wood, trees, and other refuse left in the flood areas during and after construction which have to be dealt along with the sediment or debris.

Rooted vegetation in lakes tend to trap sediments that are moving with currents and hold them in place particularly in the inshore areas. The dying or decaying plants add to the continued sediment buildup until finally the lake is inundated.

Movement of sediment

The behavior of sediment movement and deposition in lakes is largely dependent on wave action. In lakes, where waves are longer and less frequent than in reservoirs, the finer sediments such as sands, silts, and flocculent material are carried out into the lake by the waves and deposited in the lake bottom, some distant from the shoreline.

The coarser material, such as boulders, gravels, and coarse sands are left in the inshore areas. In reservoirs, which may experience short, frequent, and choppy waves, the finer materials are generally not carried out far from the shoreline but usually remain inshore and accumulate around the edges of lakes resulting in soft, muddy, or sandy shore areas.

As lakes or reservoirs start filling with sediment, wave action tends to reduce and vegetation increases, thus hastening the sedimentation of the lake. In arid zones, sedimentation is slower but because of excessive evaporation, lakes may become saline eventually precipitating inorganic salts which settle on the lake bottom.

Sedimentation in lakes usually begins with inorganic material from land sources. However, as biological production takes place, inorganic debris forms, settles, and

combines with the inorganic components of the bottom sediments. Along with this are the man-made materials which find their way to the bottom sediment in lakes. Such material may be pesticides, metals, trace elements, and other constituents which are troublesome pollutants and cause ecological problems in lake systems. These materials may enter the biological food chain through aquatic organisms, including fish, which feed on these sediments.

Suspended sediment

Suspended solids in lake waters are, in general, finely suspended particles in insoluble material including sand, silt, clay, debris from vegetable growth, algae, chlorophyll, and other buoyant-type substances. These materials originate from shore erosion through wind and wave action, tributary inputs, biological activities, and from pollution sources. Suspended solids reduce the transparency of lake waters and inhibit the penetration of light thereby reducing the photosynthetic processes and the production of oxygen. Photosynthesis is an important source of oxygen in lakes and the quantity of suspended solids in lake waters is an important factor in the organic cycle of lakes.

Transparency test of lake water

Suspended solids may be determined directly by collecting samples for standard laboratory analyses usually while carrying out water quality analyses of the lakes or rivers in the catchment. Analyses may also be determined on-site by performing turbidity tests using standard field equipment or by carrying out Secchi disk readings at the sampling location.

Secchi disk

Secchi disk readings have been used for many years to characterize the transparency of water bodies. Readings from Secchi disks may vary according to local conditions and with the observer; hence it is difficult to compare readings from different localities and by different observers. In general, Secchi disk readings refer directly to the turbidity arising from phytoplankton rather than to the vertical extinction coefficient. It is for this reason that Secchi disk readings are useful in the determination of production rates in lake waters.

Sediment accumulation and reservoir loss of storage

Reservoirs receive sediment from upstream almost continuously and release or allowance made for release as is the case in many reservoirs such as, for example, the Three Gorges Dam in China.

It is estimated that the world annual sediment discharge to the sea is as much as 13 billion tons and as much as 2.5 billion tons are trapped behind dams annually. This could mean that the estimated 6,000 km³ of world reservoir storage could be filled on average between 1,400 and 3,600 years.

Other examples of loss of storage because of reservoir sediment accumulation include Lake Mead in the USA

Lake Sediments, Table 1 Reservoir sedimentation rates and "lifetime" of reservoir (After Kobayashi, Said, and Meybeck)

Reservoir	Total capacity 10^6 m^3	Annual sediment $10^6 \text{ m}^3 / \text{year}$	Lifetime years
729 Japanese reservoirs	17,300	40.8	395
Aswan High Dam	162,000	109.0	1,600
Lake Mead (Hoover dam)	34,900	0.33%	300
World reservoirs	6,000,000	$2-5 \cdot 10^9 \text{ t/year}$	1,400–3,600

Lake Sediments, Table 2 Loss of reservoir capacity (six UK reservoirs)

Reservoir parameter	Wessenden Head	Wessenden Old	Blakeley	Butterley	Thornton Moor	Stubden
Date of construction	1881	1835	1903	1907	1885	1,868
Catchment area (km^2)	—	15,05	—	—	5,12	1,94
Original capacity (MI)	373	486	364	1,832	795	451
Revised capacity (MI)	358	321	137	1,724	702	406
Loss of capacity per century (%)	3.7	23	75.2	7.5	11.3	8.2
Annual loss of capacity (m^3)	137	1,220	2,736	1,365	895	318
Annual area-specific loss ($\text{m}^3/\text{km}^2/\text{year}$)	—	362,66	—	—	174,87	191,58

which is losing storage at the rate of some 0.33% each year implying 300 years before it is completely filled.

In the case of the Aswan High Dam in Egypt, the mean annual sediment passing through the site prior to construction was 125 million tons of which nearly all passed during floods. After construction, it was noted that only some 2.5 million tons flowed downstream of the dam. This implied that 30 km^3 of dead storage from a total dam capacity of 164 km^3 set aside for sediments in the dam would be filled in 300 years and the whole dam filled in about 1,300 years assuming conditions did not significantly change.

It is interesting to note that since the completion of the Aswan High Dam in 1964, the estuary sand bank at the mouth of the Nile retreated at least 4 km in 30 years.

Examples of reservoir sedimentation rates are given in Table 1.

During the 1976 drought in the UK, advantage was taken to study the effect of sediment accumulation on a group of six small virtually empty reservoirs in the same catchment in the Yorkshire area. The results shown in Table 2 reveal an overall loss of capacity per century of as low as 3.7% and as high as 75% with an estimated expected life of individual reservoirs in the group of between 130 and 2,000 years.

Sediment yields, however, differ from region to region. In East and Southern Asia where about two thirds of world sediments discharge into the sea, there are many reservoirs having much shorter "life" times than the examples given in Tables 1 and 2. In Thailand, for example, a number of reservoirs built for irrigation purposes were filled soon after completion with sediments derived from deforested areas. There are a number of reservoirs in Japan, mostly smaller than 10^6 m^3 built in mountainous areas

for hydroelectric power generation that experience a rapid filling of sediment, for example, within some 10 years of completion.

Recovery of storage

The methods of recovery of silted storage include flushing and emptying, siphoning, mechanical excavation, dredging, and other methods appropriate to the location.

Flushing: This usually requires outlets at very low elevation. Factors influencing flushing efficiency include geometry of the reservoir (slope, width, length, and storage capacity), amount and composition of previous deposits, and characteristics of the incoming flow and sediment.

Favorable conditions for effective flushing include:

- Steep bottom slope, narrow and small reservoir
- Unconsolidated deposits, no gravel
- High incoming discharge
- Low outlets
- Low pool level downstream

Waste of water is often the main shortcoming of flushing operation and usually is best carried out annually, the important indicator of flushing efficiency being the water–detritus (W-D) ratio, the ratio between the volume of water wasted and the volume of deposits flushed out. For many reservoirs the ratios are in the range 20–50.

Dredging

Mechanical

To remove the accumulated sediment and restore reservoir capacity, dredging of the sediment is necessary. Dredging costs can often be one of the most important costs of

reservoir operation and, depending on the reservoir size and percentage sediment accumulation, costs can be enormous.

Mechanical dredging is the major method of removing deposits of sediment from reservoirs. It consists of excavation, transportation, and disposal of the sediment. Excavation and transportation can be implemented mechanically or hydraulically and sometimes disposal may be made downstream. Mechanical excavation usually employs chain bucket, hopper wheel, shovel, grab, dipper, or backhoe dredgers.

Hydraulic

Hydraulic dredging includes cutter suction, plain suction, wheel suction, trailing suction hopper and dustpan dredgers, electric submerged pumps, and airlift pump. The transportation is by barge, pipeline, conveyer belt, cable crane, and trucks.

Siphoning

This is a special hydraulic method of dredging and consists of two parts: a dewatering device and a flexible pipeline which straddles the dam. In practice the flexible pipeline is usually connected with bottom outlets through the dam body and the pipeline and its entrance can be moved by a towing boat.

The system is widely used in small reservoirs. An example where the method is used to advantage is the Tianjiawan Reservoir in China. There a siphoning system consisting of an operating barge and a pipeline of length 229 m and diameter 550 mm was installed in 1975 to dredge the accumulated sediment. The pipeline was connected to an outlet through the dam body.

In 1977 the runoff was $4.16 \times 10^6 \text{ m}^3$ and the incoming sediment load was $2.05 \times 10^6 \text{ m}^3$. The amount of sediment dredged by siphon was $320 \times 10^3 \text{ m}^3$ with an average concentration of 190 kg/m^3 during 695 h of operation. The rate of dredging was 460 m^3 per hour therefore giving a low dredging cost.

Other methods are used, such as civil engineering works using dry-earth excavation and transportation. In practice a combination of methods for removing deposits of sediment is often proved effective.

Disposal of the dredged material is one of the major problems encountered in dredging operation, not least of which is the cost. For example, in the Netherlands it is found that $22,000 \text{ m}^2$ surface area of the disposal sites are required for each m^3/s discharge of the dredge.

Generally, there are three options for sediment disposal:

- Back into the reservoir (removing into the dead storage or near outlets)
- Onto the land (bank, valley etc.)
- Into the downstream river, but environmental requirements have to be considered
- Bypassing (diversion) channels

In Switzerland, the restriction stipulated is that a maximum of 4% sediment by volume can be mixed with

the river water. A hopeful way of disposal is to use the dredged material for industrial, agriculture, or landfill purposes. For instance, gravel dredged material has been used as concrete aggregate and sands as construction material.

Because most dams are of recent construction, sediment accumulation has not yet reached levels that seriously interfere with operations in most reservoirs. However, as reservoirs age and accumulate sediments, both the number and size of them with serious sedimentation problems is growing. Nevertheless, at many sites with serious levels of sediment accumulation, the reservoirs are not necessarily abandoned. Indeed operators seek methods of keeping the reservoirs in service by balancing sediment inflow and outflow while maximizing available benefits. This practice maintains the reservoir's "life" and its continued operation.

The loss of all the world's reservoirs due to sediment accumulation either slowly or quickly would have catastrophic results. For this reason, civil engineering practice is often to design reservoirs that will fill with sediments slowly and have a facility for containment of designed capacity.

Survey of sediment

There are basically two methods today to assess the amount of sediment accumulated or trapped in lakes and reservoirs, including a complete measurement or bathymetric survey:

- Conventional surveying method
- Electronic distance measurement (EDM) using the Globing Positioning System (GPS)

When the conventional method is chosen, it will normally be accomplished by a combination of aerial photogrammetric and bathymetric procedures. Survey normally first takes place on completion of the reservoir prior to impounding. This provides the basis to which all future surveys are compared. The conventional method using a launch equipped with echo sounder, sextant, and theodolite although formerly used for many surveys in the past is still used especially for small lakes, but now enhanced with data processor and dedicated software.

For large lakes and reservoirs, the electronic distance measurement (EDM) satellite system is now preferred employing the GPS system with one base station to serve as many roving unit outstations as necessary and equipped with receivers and data links within a 10 km radius.

Investigation of sedimentation in lakes and reservoirs

Empirical methods

As a preliminary investigation level, the sediment inflow to a reservoir may be predicted satisfactorily by applying the measured sediment accumulation rate from a nearby reservoir or another reservoir having similar catchment characteristics. Empirical methods for preliminary judgment are used generally in small reservoirs to estimate

sediment load and surface water profile. Empirical methods of study use sediment transport information such as storage ratio and hydraulic characteristics of inflow.

Mathematical model

Mathematical modeling of reservoir sediment is based on the principles of fluid mechanics, equations of motion, and continuity for water and sediment flow over a mobile bed supplemented by auxiliary equations of river sediment transport. The equations are solved under initial boundary conditions by numerical solution with simplified assumptions. Because of the diversity of sediment transport equations, numerical techniques of empirical coefficients are used.

Models are based on empirical field data of sediment transport information of rivers and existing sediment data on heavily sediment-laden rivers. However, as models rely on reliable empirical data, a properly developed and calibrated mathematical model can be used to good effect to analyze time-dependent behavior of reservoirs, and present a more complete picture of sedimentation processes including special conditions imposed by sediment sluicing and flushing operations.

Mathematical models have advanced rapidly in recent years and are generally used with confidence. However, a mathematical model often contains many empirical coefficients determined only by calibration against observed field data. A successful mathematical model addresses the following aspects:

- A knowledge of the reservoir and river to be modeled
- Reliable equations
- Suitable methods of numerical solutions

Most of the models used are classified by the terms 1-D and 2-D. It has been the practice to use model 1-D for narrow reaches and 2-D for wide reaches.

Physical model

Physical modeling has been extensively used for reservoir sediment studies for many years in some of the world's largest physical laboratories. The main questions arising concern the size and the scaling which is increasing especially in connection with important large-sized reservoirs. For example, in studies for the Three Gorges Dam on the Yangtze, a total of nine physical models were built to simulate six key reaches of total length 230 km. The horizontal and vertical scales were respectively 1/250–1/300 and 1/100–1/125. The model sediment in these models included polystyrene, bakelite, coal powders, and crushed walnut shells.

A great deal of valuable information was obtained on the prediction of sedimentation to the design of the project.

An important development is to combine physical and mathematical models and the feedback loops which exist between them. A mathematical model may be used, for instance, to provide inflows and boundary conditions for a physical model and vice versa. Also the result and

process of each may be complemented and verified. The enormous cost of physical models can usually only be supported in combination with a joint project.

Conclusion

Most river reaches are sensibly in balance with respect to sediment inflow and outflow. Dams or lakes may alter this balance and all impounded water formed by dams on natural water courses are subject to some degree of accumulation of sediment inflow and deposition which may affect this balance.

Sediments vary according to the origin of the lake and to the sediments brought down by rivers. In some cases, the economic and environmental damage of the accumulation of sediment in reservoirs can be enormous in both cost and remedial action. The sediment inflow to a reservoir is that part of the product of all erosion mechanisms at work in the catchment which enter the stream system and are transported to the lake or reservoir. In lakes this may be a small part of the total erosion ongoing in the catchment but in the case of reservoirs the financial cost can be high with respect to the loss of the value of water and the cost of remedial action which may be significant.

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Cross-references

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LAKE SHORE NOMENCLATURE

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Introduction

A recognized geomorphological nomenclature of the coastal zone is in use for a long time (Ottman, 1965;

Zenkovich, 1967; Ellis, 1978; Davis, 1982), which is not the case for fluvial and lacustrine milieus. In fact, for these milieus, the specialists have developed a specific nomenclature for each discipline. But the coastal or the fluvial nomenclature is too often applied without distinction to the lacustrine milieu. To our knowledge, the only book entirely dedicated to lacustrine terminology is the one of Veatch and Humphrys (1964), but it is incomplete. As the three mentioned milieus are submitted to different conditions and processes, their nomenclature should be different (Mailhot et al., 1985).

Particularities of the coastal, lacustrine, and fluvial milieus

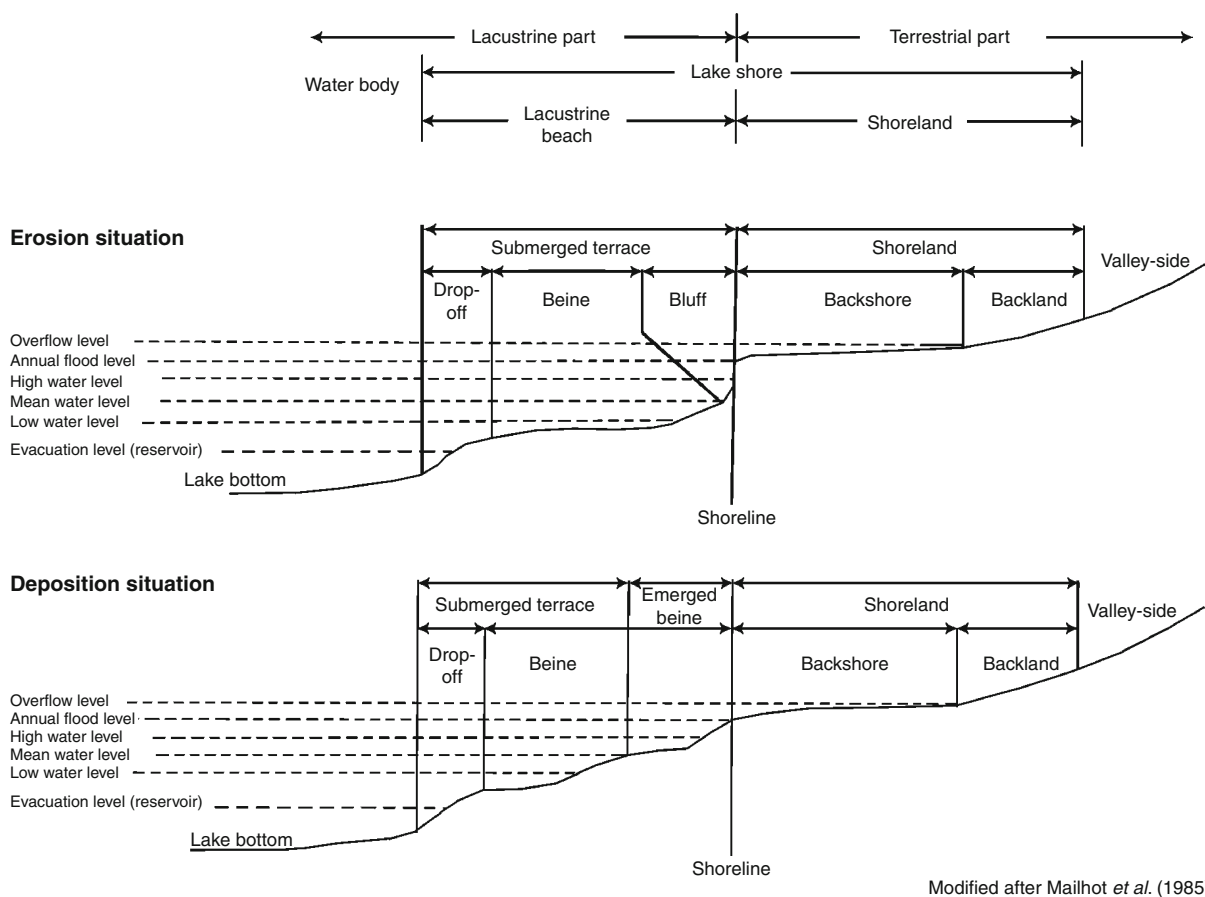
The coastal and estuarine zones, the lakeshore, and the valley bottom are terms designating the shore zone, which is the area on both sides of the shoreline under the influence of currents, overflow waters, tides, or waves. The shore zone invariably includes terrestrial and aquatic parts which are under the influence of different water levels. The lower and the upper limits of the shore zone are delineated by extreme water levels.

Mailhot et al. (1985) have proposed a specific nomenclature for coastal, lacustrine, and fluvial milieus which are affected by specific dynamics. The coastal milieu is characterized by daily fluctuations of the water by tides and by important wave amplitude mainly during spring tide and storms. The lacustrine milieu is characterized by seasonal fluctuations of water level and by the wave action limited by the wind fetch. This wind fetch rarely allows the formation of important waves except for major lakes like the Great Lakes. Finally, the fluvial milieu is affected by the discharge which generates the water flow and also by the fluctuations of the water level in relation with the floods. The height of the floods depends on the watershed morphology and on the hydrologic regime.

The nomenclature of the shore zone is complex, considering the fact that the specialists of each discipline have developed their own vocabulary. Thus, geomorphologists, biologists, limnologists, planners, and lawyers name differently the components of the shore zone in accordance with their knowledge and concern in relation with the considered milieu. By example, the limnologist defines the lower limit of the shore zone in regard with the lightness. The decline of the lightness with the water depth influences the distribution and the growth of aquatic plants (Wetzel, 1983). On the other hand, the geomorphologist defines this limit in regard with the wave action which is responsible of the formation of the drop-off in a lake.

The basic elements used to create the different nomenclatures are:

- Terrain forms resulting from the currents and wave action (geomorphologists)
- Trophic stage of the aquatic milieu (biologists and limnologists)
- Potential use of the shore zone (planners)
- Laws and regulations related to the private property and environmental protection (lawyers)



Lake Shore Nomenclature, Figure 1 Lake shore nomenclature for geoscience specialists.

Lake shore geomorphological nomenclature

The terrestrial milieu of lake shore zone corresponds to the shoreland and to the valley side, and the lacustrine milieu corresponds to the lacustrine beach. In the shore zone, three geomorphological divisions are related to the water level fluctuation: backshore, emerged beine, and submerged terrace.

The limits of these divisions are respectively the overflow level related to exceptional floods, the annual flood level occurring at the period of highest precipitations or at the spring melt out of the snow cover, the mean water level, and finally the foot of the drop-off. The shoreline, dividing the lacustrine and aquatic milieus, corresponds to the high water level related to usual water level.

Lake shoreline

The lake shoreline corresponds either to an erosion talus or to a depositional form (Figure 1) in relation to the wave action budget on each part of the lake periphery.

Excluding karstic and endorheic lakes, which have variable levels, the lake shoreline is generally stable at the human observation time scale because it is under the control of the outlet. In natural conditions, the lowering of the

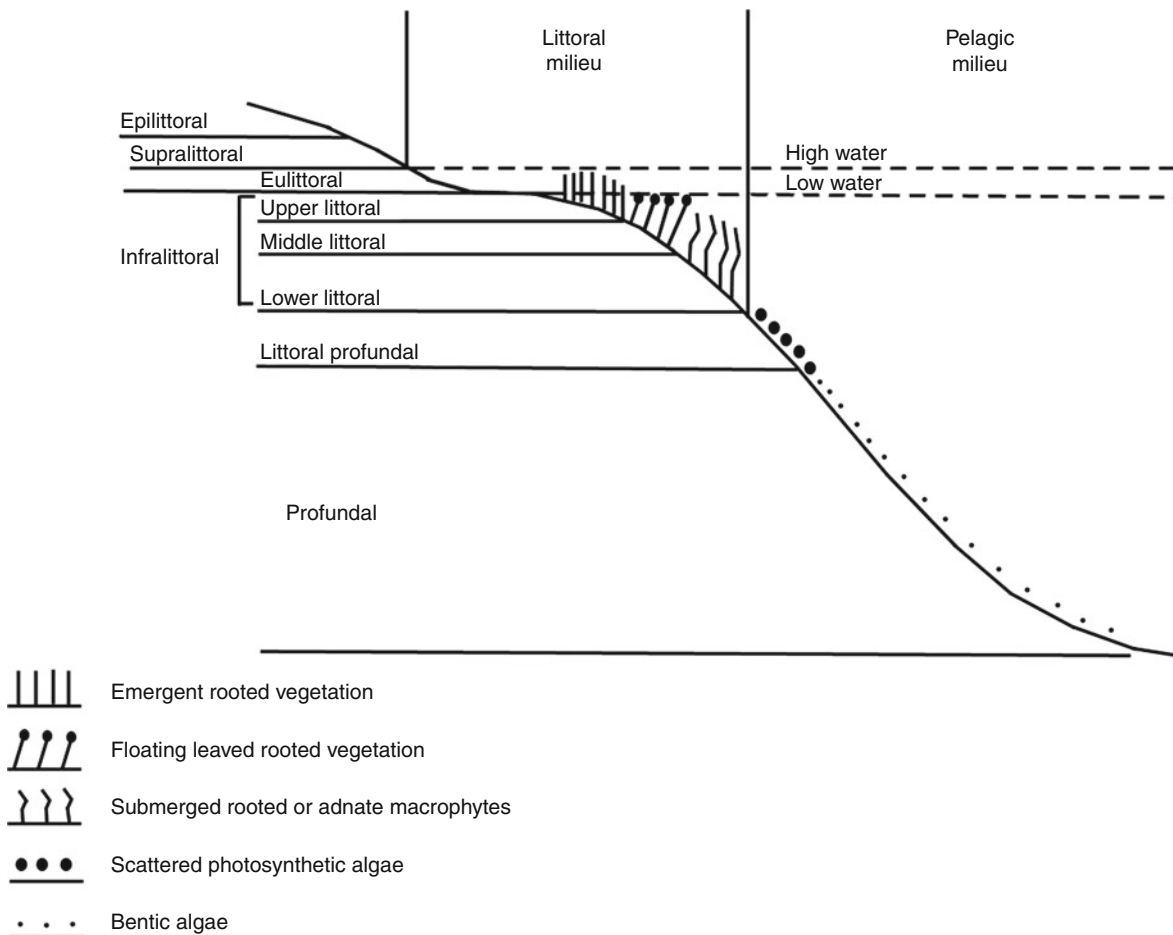
outlet is gradual or in jerks and results only from the regressive erosion processes. On the other hand, the rare cases of natural heightening of the outlet result from lava flows, mass movements, glacier surges, beaver dams, etc. The more frequent cases of outlet heightening are human made, like the setting of dams for hydroelectric production or the regulation of hydrologic regime of streams and lakes.

In a long-term period, the shoreline can be modified by sediments deposition (deltas), by the encroachment of the vegetation (peat bogs, marshes) caused by lake eutrophication or by man-made encroachment.

Lake shore terrestrial milieu

The terrestrial milieu of the shore zone includes the backshore beyond which extends the backland, if the slope of the surface is similar to the slope of the backshore, or the valley-side, if the slope becomes steeper.

The backshore is only slightly influenced by the waves' action. The low occurrence and short period of overflow do not allow any particular shaping of this part of the shore zone. A microtalus or high-water marks made of vegetation debris can occur at the overflow limit (Vachon *et al.*, 1997).



Modified after Wetzel (1983)

Lake Shore Nomenclature, Figure 2 Lake shore nomenclature for biologists and limnologists.

If the overflow water is muddy, the surface of the backshore can be silted.

The backshore is often humid because it corresponds totally or partially with the resurging area of the phreatic water table.

Lake shore lacustrine milieu

The geomorphology of the aquatic part of the shore zone is different according to the presence of erosion or deposition processes. In an erosion situation, a bluff replaces the emerged beine occurring in a deposition situation.

In an erosion situation, the aquatic part corresponds to the submerged terrace divided in three parts: the bluff, the beine, and the drop-off. The bluff, resulting of wave action, is located between the annual flood level, corresponding to the shoreline, and the mean water level. The beine corresponds to an erosion surface in its proximal part and to a deposition surface in its distal part. The beine is located between the mean water level and the

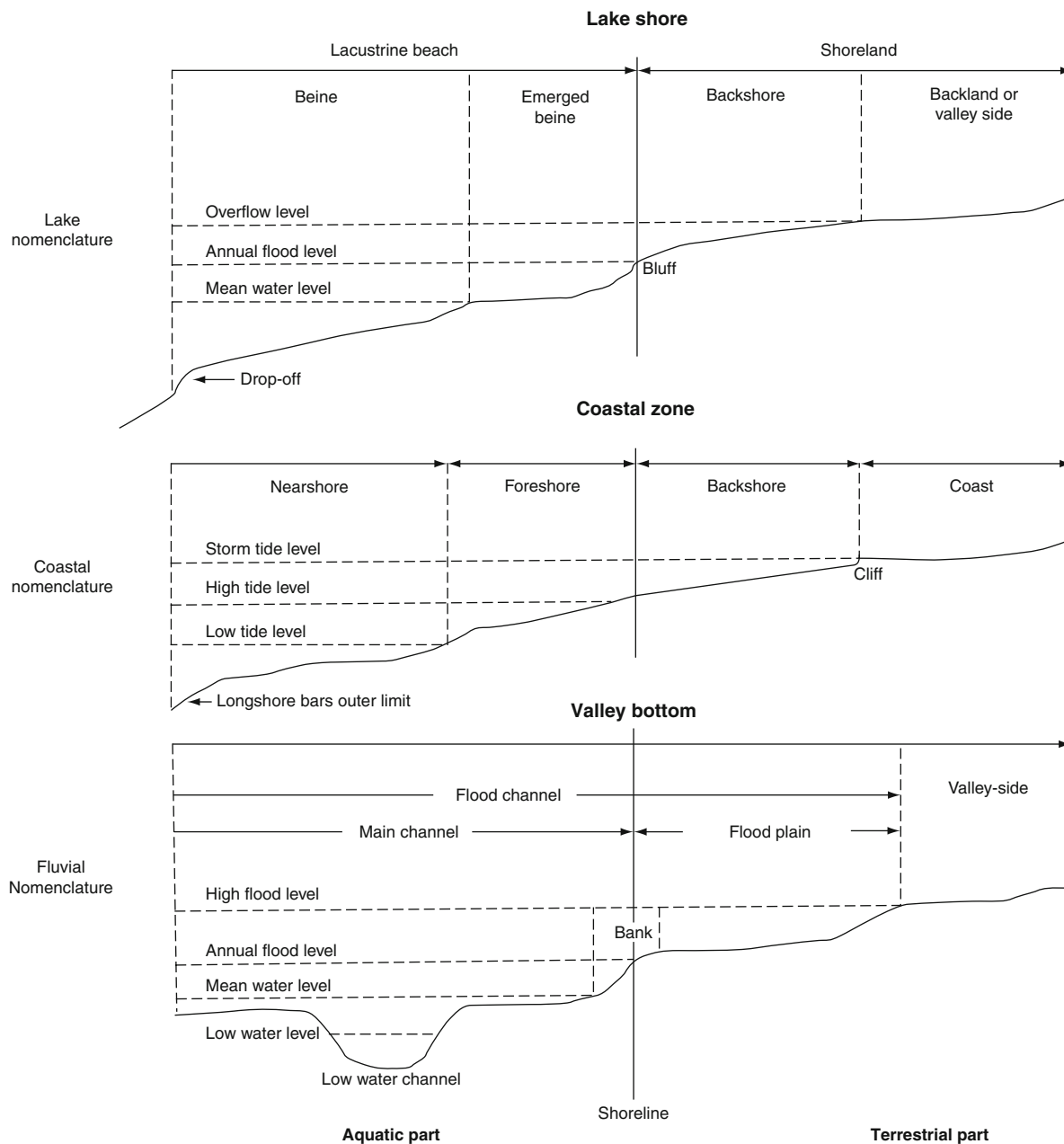
inferior limit of the wave action corresponding to the upper limit of the drop-off. The drop-off is built by sediments carried by waves towards the lake bottom.

In a deposition situation, the aquatic part includes the emerged beine and the submerged terrace. The emerged beine is located between the annual flood level, corresponding to the shoreline, and the mean water level. The emerged beine results from deposition processes which extend to the submerged terrace. The submerged terrace includes the beine and the drop-off, similar to the erosion situation. The only difference is that the beine is the result of sediment deposition.

Biologists' and limnologists' nomenclature

Biologists and limnologists use a different nomenclature for the lacustrine milieu. This nomenclature is based on zonation of vegetation (Figure 2).

The delimitation of the different zones is justified by the distribution of vegetation types in accordance with the



Modified after Veatch and Humphreys (1964), Loup (1974), Dubois (1979), Mailhot *et al.* (1985), Greenwood (2005) and Chrzastowski (2005)

Lake Shore Nomenclature, Figure 3 Comparative nomenclature of lake shore, coastal zone, and valley bottom.

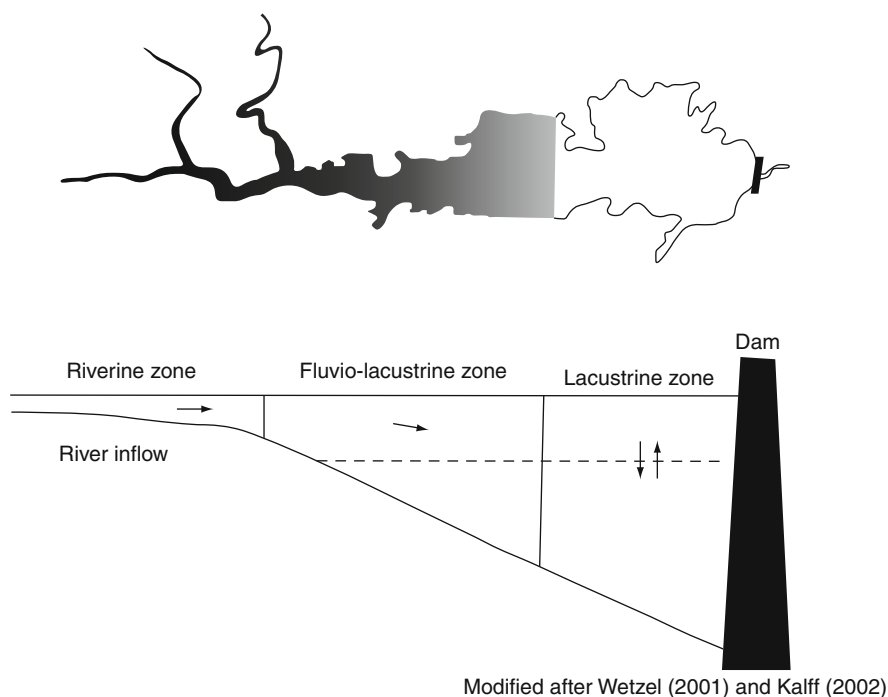
decline of the lightness in the water (Hutchinson, 1967). The vegetation of the “littoral” milieu changes gradually from riparian species between low and high waters (eulittoral) to rooted species which are emergent, floating-leaved, or submerged in the infralittoral. The vegetation of the pelagic milieu is mainly composed of different algae species.

The nomenclature used by biologists and limnologists is completely different from the one used by geoscientists.

In particular, we notice that biologists and limnologists improperly use the coastal term “littoral” instead of lake shore.

Planners’ nomenclature

The nomenclature used by planners is limited to the difference between dry beach and wet beach (Veatch and Humphrys, 1964). The limit between the two zones



Lake Shore Nomenclature, Figure 4 Reservoirs zonation terminology.

approximately corresponds to the mean water level, corresponding to the shoreline. This elementary nomenclature is justified by the different recreational activities practiced in the terrestrial and aquatic milieus (Provencher and Thibault, 1976).

Comparative nomenclature of lake shore, coastal zone, and valley bottom

The shoreline is the only common term used, with the same signification for the three milieus (Figure 3).

In fact, in each milieu, the shoreline corresponds to a high water level: the annual flood level for lakes and rivers and high tide level for the coast. Almost all the other terms are specific to each milieu as the geomorphologic and ecologic processes are different.

Transition situations exist between the fluvial and lacustrine milieus as well as between fluvial and coastal milieus. It is particularly the case for reservoirs where the elevation of the water level results in the widening of the downstream part of tributaries to create a fluvio-lacustrine zone (Figure 4).

In such cases, the terminology will gradually change from lacustrine to fluvial.

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Cross-references

[Sedimentation Processes in Lakes](#)

[Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes](#)

LAKE SURVEYING

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Synonyms

Lake bathymetry; Lake morphometry

Definition

Profiling: A survey that provides a cross section along a line across a lake.

Mapping: A survey that covers a horizontal area, just like a conventional map.

Bandwidth: The frequency range used by the instrument. A larger bandwidth provides better range resolution.

Aperture: The size of the transducer measured in wavelengths. In that respect a large transducer generates a narrow beam-width.

Penetration: The capacity of a sonar to reveal sedimentary features below the bottom.

Footprint: The area on the bottom which is illuminated by the sonar and may produce an echo.

Introduction

The original method for lake surveying is by using a rope and a weight. Often this rope carries knots at regular intervals. The pseudonym “Mark Twain” refers to the second knot on the rope equal to a depth of two fathoms, the once necessary navigation depth for a steamer on the Mississippi River. Positioning on lakes could be made by sight-lines to pairs of objects ashore, which permits very precise navigation along a straight line. Another possibility for positioning is to make measurements from holes through the ice, if such conditions exist. Today lake surveying is usually done with different types of sonars, transmitting and receiving reflected acoustic energy.

This equipment is the same as is used for surveying of the sea. Navigation and positioning is left to the Global Positioning System (GPS) or any of the other similar systems based on satellite data. The advent of the digital computer facilitates mapping of lakes in that it is not necessary to measure in a regular grid to facilitate manual interpolation. Any pattern will do and the navigation plot will tell the operator that all parts of the lake have been surveyed.

Lake surveying differs from marine surveying in that lake water is less conducting than seawater and thus in many cases permits the use of radio waves as a complement to acoustic and light-waves that work in both types of water.

In addition to the physical principle used, it is also relevant to separate the survey methods into profiling and mapping methods. In the profiling method, the depth of the water and possibly the structures of sediments and even rock are measured along a line, giving a 2-D output (length, depth), while in the mapping method the output is in 2-D (length, width) or in 3-D (length, width, and depth). The dimensions referred to here are the geometrical ones. In addition there is a radiometric dimension, which is the strength of the bottom echoes. There may also be a spectral and a temporal dimension in survey data. A spectral dimension occurs if the transmitted pulse is of a wideband nature and a temporal dimension is created by repeating a survey along the calendar time axis. Mapping can of course also be performed by surveying many parallel profiles.

All described methods are based on the transmission of pulses and recording of echoes emanating from objects and structures of interest to the surveyor, the echo delay generating information about range. A significant property is the beam-width radiated. It is determined by the aperture size in wavelengths. A large aperture in this respect creates a narrow beam. The illuminated part of the lake bottom is the footprint of the sonar. Any object within the footprint that has a geometric normal pointing toward the transducer will be able to generate a recorded echo.

Profiling 2-D: the echo sounder

The most common instrument for lake mapping is the echo sounder, which covers both the sonic and ultrasonic frequency ranges. A pulse is transmitted toward the bottom and echoes are recorded and presented as a profile. Such a pulse is often called a ping. Since the velocity of sound waves in water is known to be about 1,500 m/s, the recorded time of echoes can be transformed into distance by a simple operation. For more precise requirements there are special probes that can be lowered to get a velocity profile in the water column. Generally sonic instruments, which operate below 20 kHz per definition, give penetration into the sub-bottom layers revealing the structure of the sediments. A known problem is the presence of gas bubbles in sediments, which will decrease penetration of acoustic waves. Ultrasonic instruments provide higher lateral resolution of bottom surface features because the transmitted beam can be made sharper

with a similar size transducer and also the pulse length can be made shorter to provide higher vertical resolution. Only very soft bottom sediments – mud blankets with properties much like water – are penetrated with ultrasonic waves. The ultrasonic echo sounders generally operate below 200 kHz. The echo sounder can be deployed from any craft of opportunity.

Profiling 2-D: the parametric sonar

The parametric sonar takes advantage of the nonlinearity of water. If a very strong high-frequency pulse is transmitted there will be a leakage into a lower frequency range. The interesting thing with this low-frequency pulse is that it will have the same beam-width as the high-frequency pulse. A parametric sonar thus can present a precise echo from the lake bottom and surface sediments using the high-frequency echoes, while the low-frequency echoes would reveal deeper structures in the lake bottom. It is of particular interest that those two profiles, contra-intuitively, would have the same horizontal resolution. The reason for this is that the conversion from high to low frequency takes place only within the high-frequency beam. Also the parametric sonar allows low-frequency sounding to be made with rather light equipment. The minimum depth required for the parametric effect to develop is usually in the range of a couple of meters. The parametric sonar can be deployed from any craft of opportunity.

Profiling 2-D: the ground-penetrating radar, GPR

In low conductivity freshwater radar is a feasible method for bathymetry and sub-bottom profiling. The useful frequency would be about 100 MHz. The speed of electromagnetic waves in freshwater is about 0.033 m/ns. The range increases with lower frequency and lower electrical conductivity of the water. Resolution is improved with a higher frequency. Due to the nature of electromagnetic waves gas bubbles may be a lesser problem with radar than with an acoustic sounder. The GPR pulses are always of a wideband nature, which makes spectral signatures feasible to obtain, thus helping in bottom classification. For mapping sub-bottom features in deep lake water a borehole antenna can be used. It would be towed behind a boat in a cable with the antenna just above the bottom in order to reduce the attenuation in the water. A very practical feature of using radar is that profiling could be made through ice if such is present. Navigation is greatly simplified by this tactic. Obviously profiling of freshwater ice thickness is also possible with radar. For that purpose higher frequencies would be chosen. For mapping freshwater ice thickness 500 MHz could be used with the antenna installed in a helicopter. The GPR can be deployed from any craft of opportunity.

Mapping 2-D: the side-scan sonar

The side-scan sonar is, in principle, an echo sounder turned sideways, albeit with a different radiation pattern known as a vertical fan-beam illuminating the bottom

sideways. Thus the arrival time of echoes are converted into lateral distance (range) instead of vertical distance (depth) as it is in the echo sounder. The image is built up in the same way as a television image, by adding line after line to form a 2-D image, each line produced by a new ping. One dimension is created by the forward movement of the craft, the other dimension by the echo-time converted to slant range distance. In order to create an image with good resolution it is desired to project an ultrasonic fan-beam which is very narrow in the direction of travel. A side-scan sonar tow-fish, containing port and starboard transducers, is pulled in a cable behind a boat to make the trajectory smooth. By varying the tow-fish altitude over the bottom different shadow effects are obtained. A trajectory close to the bottom will generate longer shadows from objects protruding above the bottom than a higher trajectory will do. The shapes of shadows behind such objects often tell more about the objects than the direct echoes do. Depending on the frequency chosen there will be different backscattering from different types of bottoms, thus making it possible to map the extent of, e.g., rocky vs. sandy or gravel bottom. Since time is converted to slant range it cannot also be converted to depth. This means that a side-scan sonar cannot be used to measure the depth of sub-bottom features. A strongly protruding object (proud object) would be mapped closer to the sonar than the real distance. Sub-bottom features may be recorded, however, but depth would be added to range. A possible discrimination method is to use a high-frequency image to record bottom features and a low-frequency image to identify sub-bottom features in addition. The difference image would indicate only sub-bottom features. Side-scan sonars are operated from a few kHz to one MHz, with ranges between tens of meters to tens of kilometers. High-frequency systems could be deployed from any craft of opportunity.

Mapping 2-D: the sector-scan sonar

A special kind of side-scan sonar has a small side-scan transducer that rotates around a vertical axis and creates an image by plotting the echoes on a Polar Plot Indicator (PPI), just like the archetypal radar screen. This kind of sonar is often used on underwater robots for detection of objects and is normally operated above 500 kHz. The radial range may be 50–100 m. Modern systems use electronic scanning of the beam. It may be useful to lower this type of sonar through a hole in ice. Before the advent of the multi-beam sonar (see below), PPI-sonars could be used with the rotating axis horizontal and oriented in the direction of travel, in order to produce a sequence of lateral profiles of the bottom topography. Due to the high frequencies used, no penetration into bottom sediments is expected. The sector-scan sonar can be deployed from any craft of opportunity.

Mapping 2-D: the synthetic aperture sonar, SAS

In a side-scan sonar the narrow beam-width in the direction of travel is produced by having a transducer that is

long relative to the wavelength in the same direction. For very high resolution at low frequencies the length of the transducer would render the tow-fish impractically long. In order to overcome this problem the synthetic aperture sonar combines the echoes from 10 to 100 subsequent pings to computationally generate an image with range independent and very high azimuth resolution. All of the used pings must illuminate a given target, which requires a wide beam and thus, contra-intuitively, a rather small transmitting transducer is used. The range resolution is only affected by the bandwidth of the transmitted pulse, which is often a chirp, which is a frequency sweep within the ping. The reconstruction process requires very precise information about the transducer orientation for each ping, thus making it necessary to add expensive positioning equipment. The SAS requires permanent installation in a suitable craft.

Mapping 3-D: the multi-beam sonar

The multi-beam sonar can be thought of as a number of echo sounders in parallel. Each receiver covers a laterally displaced track on the bottom but there is only one ping transmitted. The unique outcome is a 3-D data set showing the bottom topography in a swath under the ship. This kind of sonar utilizes digital signal processing to form the different beams. The survey must be supported by a GPS system and a Motion Reference Unit (MRU). All information is thus geo-coded and this kind of sonar is now dominating in the production of bathymetric maps. The multi-beam sonar requires permanent installation in a suitable craft.

Mapping 3-D: airborne laser

Small water depths are often difficult to measure using a boat as a vehicle. For such situations, e.g., in the beach zone, airborne laser may be an alternative to walking around with a GPS on a stick. It works much like the multi-beam sonar but with light. A short, usually green, laser-light pulse is transmitted at different lateral angles from the nadir direction, thus producing a swath of depth measurements perpendicular to the direction of flight. For each angle a new pulse is transmitted. When many such swaths are generated along the flight track a 3-D data output is obtained. There is one echo from the surface of the water and a second echo from the bottom. The water has to be optically transparent. Special inertial and GPS equipment must be used to remove the trajectory of the aircraft and to geo-code the data.

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Cross-references

[Bathymetrical Survey of the Scottish Freshwater Lochs, 1897–1909](#)
[Satellite Data and Lakes](#)

LAKES AS ARCHIVES OF EARTH HISTORY

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Synonyms

Limnogeology; Paleolimnology

Definition

The sedimentary record preserved in lakes and ancient lakes provides an archive of past climatic and environmental changes.

Lakes as archives of earth history

Lakes have existed and vanished throughout Earth's history, but their traces have been preserved in the form of sedimentary rocks, sediments, and shorelines (see "[Lake Sediments](#)", "[Classification of Lakes from Origin Processes](#)", "[Age Determination of Lake Deposits](#)"). All lakes have been and are subject to a variety of external and internal forcing variables that regulate the subsequent history of the lake, such as climate, bedrock composition in the catchment, tectonic and volcanic activity, vegetation, aquatic biota, and human activities (see "[Lakes on Earth, Different Types](#)", "[Stratification in Lakes](#)", "[Sedimentation Processes in Lakes](#)", "[Climate Change Effects on Lakes](#)"). These variables or traces of these are preserved in the sediments and sedimentary rocks and form excellent physical, chemical, and biological markers to reconstruct climatic and environmental changes using different types of analytical methods. Ancient lacustrine sedimentary rocks moreover form important hydrocarbon sources. The study of these changes in space and time is termed limnogeology and/or paleolimnology (see "[Paleolimnology](#)").

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Dead Sea
Paleolakes
Paleolimnology
Sedimentation Processes in Lakes

LAKES ON EARTH, DIFFERENT TYPES

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Introduction and aim

Hutchinson (1957) has discussed all major lake types, their origin, morphometric characteristics, and distribution on Earth. He differentiated among 11 major lake types that were divided into 76 subtypes. The 11 major lake types are summarized in Table 1. Most lakes on Earth appear in glacial landscapes. The aim of this short paper is to summarize the main characteristics of these major lake types, and most of these descriptions emanate from Håkanson (1981) (Table 2).

Results

As for biological species, lakes exist in three successive stages; youth, maturity, and old age. Lakes generally originate from drastic geological events, such as volcanism, earthquake, or glaciation. The relief of the drainage area and the lake basin is under ongoing alteration by exogenic forces, e.g., weathering, erosion, transport, and accumulation. Most lakes in northern Europe and North America have been influenced by the great form-creating power of the latest, but not last, glaciation. If there are no future tectonic catastrophes, all these lakes will in due course be filled up by sediments and transformed into land. The 11 major lake types on Earth are:

1. Tectonic lakes formed by movements of the deeper part of the Earth's crust, e.g., lakes form by tilting, folding, or warping, such as the Central African Rift lakes. Some of the largest lakes on Earth belong to this category. The Caspian Sea, the Sea of Aral, and other lakes from the Pontocaspian area have been separated from the sea by several land elevation events. Also the mountain-building events that created also the Alps produced lakes of this category.
2. Volcanic lakes, e.g., maars, calderas, and crater lakes, as well as lakes formed by volcanic damming

Lakes on Earth, Different Types, Table 1 Major lake types on Earth according to Hutchinson (1957)

1. Tectonic lakes, e.g., basins in faults (like Lake Bajkal and Lake Tanganyika).
2. Volcanic lakes, e.g., maars, caldera lakes and lakes formed by damming of lava flows.
3. Landslide lakes, e.g., lakes held by rockslides, mudflows, and scree.
4. Glacial lakes:
 - A. lakes in direct contact with ice, e.g., lakes on or in ice and lakes dammed by ice.
 - B. Glacial rock basins, e.g., cirque lakes and fjord lakes.
 - C. Morainic and outwash lakes, e.g., lakes created by terminal, recessional, or lateral moraines
 - D. Drift basins, e.g., kettle lakes and thermokarst lakes.
5. Solution lakes, e.g., lakes formed in caves by solution.
6. Fluvial lakes:
 - A. Plunge-pool lakes.
 - B. Fluvial dams, e.g., strath lakes, lateral lakes, delta lakes, and meres.
 - C. Meander lakes, e.g., oxbow lakes and crescentic levee lakes.
7. Aeolian lakes, e.g., basins dammed by windblown sand and deflation basins.
8. Shoreline lakes, e.g., tombolo lakes and spit lakes.
9. Organic lakes, e.g., phytogenic dams and coral lakes.
10. Anthropogenic lakes, e.g., dams and excavations made by man.
11. Meteorite lakes, e.g., meteorite craters.

3. Landslide lakes are created by mudflows, rockslides, and scree
4. Glacial lakes; there are very many types of glacial lakes, and it is often difficult to give clear-cut distinctions between glacial lakes and lakes influenced by other activities. The following main types of glacial lakes may be identified:
 - Lakes in direct contact with ice, e.g., lakes on ice or lakes dammed by ice.
 - Glacial rock basins, e.g., sub-alpine (or piedmont) lakes, cirque lakes or fjord lakes. To this category belong lakes of the English Lake District, lakes Geneva, Constance and Brienz in the European Alps, the Great Slave Lake in Canada, the fjord lakes in Norway (e.g., Mjøsa) and the Laurentian Great Lakes in Northern America.
 - Morainic and outwash lakes, e.g., lakes created by terminal, recessional and lateral moraines.
 - Drift basins, e.g., kettle lakes and thermokarst lakes.
5. Solution lakes. The famous region for solution lakes is the Karst area along the Dalmatian coast, but solution lakes exist also in Florida. The water percolation deposits of soluble materials such as limestone and gypsum may produce cavities and lakes of this type.
6. Fluvial lakes are produced by running water, e.g., plunge pool lakes, fluvial dams and meander lakes
7. Aeolian lakes are produced by wind action mainly in arid environments, e.g., deflation basins and lakes dammed by windblown sand (loess)
8. Shoreline lakes are generally created by longshore currents, e.g., tombolo lakes and spits lakes

Lakes on Earth, Different Types, Table 2 Morphometrical data for the four largest Swedish lakes (From Håkanson, 1981)

	Vänern	Vättern	Mälaren	Hjälmarén
Total area (km ²)	5,893	1,898	1,617	492.9
Open water area (km ²)	5,648	1,856	1,096	477.8
Volume (km ³)	153	74.0	14.0	2.89
Maximum depth (m)	106	128	63	22.0
Mean depth (m)	27.0	39.8	12.8	6.05
Large islands (> 1 km ²), number	20	6	43	4
Total area (km ²)	177.8	36.2	9.03	9.03
Islands (1–0.01 km ²); number	793	81	354	95
Total area (km ²)	54.7	4.65	4.51	4.51
Small islands (1–0.01 ha); number	8,772	813	1,248	963
Total area (km ²)	11.8	0.96	1.21	1.21
Rocks (< 0.01 ha); number	12,100	10,999	6,584	14,546
Total area (km ²)	0.58	0.52	0.31	0.36

9. Organic lakes are a relatively small category of lakes, e.g., beaver dams, coral lakes, or dams formed by vegetation
10. Anthropogenic lakes are formed by the activity of man
11. Meteorite lakes are created by the drastic impact on earth by meteorites

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Cross-references

[Classification of Lakes from Hydrological Function](#)
[Classification of Lakes from Origin Processes](#)
[Origin of Lakes and Their Physical Characteristics](#)
[Paleolimnology](#)
[Russian Lakes](#)

LARGE DAMS AND ENVIRONMENT

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Introduction

Rainfall is the most variable component of the hydrological cycle. Oftentimes, rainfall does not occur when it or where it is needed. The construction of a dam creates a reservoir where water can be stored during wet periods and saved until it is needed during dry spells.

If reservoirs are connected to form a network, they can be used to overcome some of the problems caused by the spatial variability of rainfall.

The first dams were constructed some 5,000 years ago, on the Euphrates and Tigris rivers in Mesopotamia and on the Nile in Egypt. The pace of dam construction was, however, not very fast. According to the International Committee on Large Dams (ICOLD), there were less than 500 dam at the end of the nineteenth century. Of them less than 10 could be classified as large dams. Postel (1993) claims that it was not until two centuries ago that the science of irrigation, grounded in the principles of hydraulics, took root. In 1800, an estimated eight million hectares, an area about the size of Austria, were equipped with watering facilities. A number of large projects constructed during the nineteenth century, especially in India and what is now Pakistan, brought the total area irrigated in 1,900 t about 48 million hectares.

As world population grew from 1.6 billion to more than five billion over the past 90 years, irrigation became a cornerstone of global food security. The higher yields farmers could get with a controllable water supply proved vital to feeding the millions added to our numbers each year, especially as opportunities to cultivate new land dwindled. The so called Green Revolution was based on high yielding varieties of seeds or modern varieties of seeds, as many scholars prefer to call them. They think that the term high yielding will make people believe that are high yielding under any condition. However the high yields require fertilizers and controllable water. The importance of fertilizer in this production system explains why the Green Revolution is sometimes termed the “seed-fertilizer revolution” and, in the same way, the phrase “blue revolution” has been used to point at the central role of controlled water (Karim, 1986).

In the first half of the twentieth century, the focus of river organizations was concentrated on irrigation, hydro-power, and flood protection. People believed in the “domination of Nature paradigm” and the common belief was that every drop that went to the sea was a lost drop. When people started to question this paradigm in the 1960s, they became more unhappy about the environmental impacts of large dams.

Although the first clash between dam developers and environmentalists started already in 1903 around the construction of the Hetch Hetchy Dam in Sierra Nevada, it was not until the 1970s that academics started to write about the issues. One example is “The Careless Technology” (Farvar and Milton, 1973). Here, there is a contribution by Kenneth E. Boulding, the economist who invented the concept of Spaceship Earth (Boulding, 1965).

His contribution is “A ballad of Ecological Awareness.” The first line reads:

The cost of building dams is always underestimated –
and the last three lines read:

So cost-benefit analysis is nearly always sure.
To justify the building of a solid concrete fact
While the Ecologic Truth is left behind in the Abstract.

In the ballad, he also mentions problems like farmlands and forests submerged by the reservoir, waterlogging, diminishing fish stocks, siltation, and the increasing amount of infected snails and waterborne diseases.

An emerging awareness of the environmental problems

It was not until the UN 1977 Water Conference in Mar del Plata that there was a global assessment of the state of water resources and water management. The result was quite shocking, and the result was a call for “Integrated Water Resources Management” and an upgrading of river basin organizations.

It is fair to say that it was not until after this conference that environmental and social impact assessments were included in dam project appraisals. By then, 35,000 large dams out of the 45,000 we have today had already been constructed. No wonder then that the world is faced by a host of dam-related environmental problems.

Loss of habitat

It is not just people that are displaced by the reservoirs created by large dams. Bardach and Dussart (1973) assert that “most species of large and small game have territories, home ranges, and feeding circuits associated with the main stream of a river or its tributaries.” “It is this habitat, of course, that a dam floods. Since the majority of animals cling tenaciously to their home grounds, the arrival of (the flood of waters) spells death for most territorial creatures.”

Thus, the Three Gorges project on the Yangtze River not only endangers the Chinese River Dolphin and the Chinese Alligator, but also the Chinese Tiger, the Siberian Crane, and the Giant Panda (O’Hara, 2005).

Downstream water shortage problems

Damming and profligate water use make many rivers periodically fail to reach the ocean. Examples of affected rivers are the Yellow River in China and the mighty Ganges (Hjorth, 2001).

When the Hoover Dam and Lake Mead filled, there was hardly any river water reaching the Colorado River estuary for almost 6 years (Rodriguez et al., 2001). Later,

when the Glen Canyon Dam and Lake Powell filled, there was a similar problem. Now, the Sierra Club (2000) claims that the Colorado River no longer reaches the sea and that its delta has been converted to a dry salt flat.

Another example is the High Aswan Dam on the Nile. The construction of this dam drastically changed the downstream conditions. There were no more any floods and no silt in the water. As the irrigated area was not expanded after the dam construction, farmers could apply more water to the land they were already cultivating. As a result, the return flows from the farmlands to the Nile became more salty and the Nile water became more saline (White, 1988).

It seems that much of the salinity of the Nile is deposited in the Nile Delta as the outflow to the Mediterranean has the same salinity as before the dam construction. Another effect is that the delta has become much smaller due to the lack of silt in the water. As the amount of nutrients in the water flowing into the sea has been reduced, the annual landing of the sardine fishery in the eastern part of the Mediterranean has been reduced from 18,000 t to 3,000 t. However, it is not firmly established that all of this decline can be blamed on the Aswan Dam (White, 1988).

Changes in the aquatic environment

The damming of a river generally causes important changes of the aquatic environment. As a flowing river reach is converted to a lake, many of the existing fish species may be outcompeted by other species that are better adapted to the lacustrine (lake) regime.

As the reservoir will submerge farmland, forests, and human settlements, there will be exchange processes that will impact the chemical composition of the reservoir water. This will have an impact on the selection of species that will thrive in the reservoir.

If the reservoir area is not effectively cleaned before the reservoir filling starts, the biomass on the bottom of the reservoir will start to decompose, a process that consumes much oxygen. The result is that the oxygen in the bottom layers will be used up, and there will be a production of H_2S , which is poisonous to fish. If bottom water is released from the reservoir, there may be significant fish kills downstream of the dam.

The water temperature is most likely to change as the heat exchange processes for a large and deep water body is different from that of a shallow running stream.

The fluctuating water table in the reservoir may prevent littoral areas to be used as spawning grounds. As the reservoir traps all sediments that enter it, the downstream erosion pattern will change, which may affect existing spawning grounds downstream.

Environmental flows

In their natural state, most rivers have periodical flooding events. Dams tend to eliminate these flooding events. One example is the Hoover Dam on the Colorado River. This river had experienced natural flooding before the construction of the dam eliminated the natural floods, which

imperiled many species adapted to the flooding, including both plants and animals (Schmidt et al., 1998).

Covich (1993) noted that if the water of a reservoir is used only to optimize the amount of irrigation water or hydropower production, the downstream environment may suffer great damage. This has now been widely understood, and a new research area has been developed, Environmental Flows. According to the global Environmental Flows Network (eFlowNet), environmental flows refers to water provided within a river, wetland, or coastal zone to maintain ecosystems and the benefits they provide to people (eFlowNet, n.d.).

The failure of bioengineering

Dams prevent fishes to swim upstream to their spawning grounds, and fish swimming downstream may get crushed in the hydropower turbines. The Columbia River is a case in point. It used to be the richest US salmon river outside Alaska. Now, it is almost completely harnessed with dams from the headwaters in Canada down to the Bonneville dam in the lower reaches. Together with its tributary Snake River it is a classic example of failure to solve fish-versus-dams problems.

Fishery biologists and administrators bitterly opposed the high-dam construction projects and predicted the fishery would be ruined if the plans materialized.

The engineers confidently assumed that, thanks to advances in devising fish-passage facilities at the high dam, we could “fish and power too” on the Columbia.

With 50 years of hindsight, it is easy to see that the biologists were right and the engineers wrong. Despite the expenditure of more than \$500 million in fish-ladders, bypasses and allied facilities, and a vast restocking program, much of the salmon habitat in the river has been lost and the runs of major species have greatly declined. It is estimated that, between 1960 and 1980 alone, the loss of fish was worth \$6.5 billion (Netboy, 1986).

Aesthetic or recreation values can also be an issue. The early conflict mentioned above was about the construction of the Hetch Hetchy Dam, which was primarily intended to supply water and electricity to the city of San Francisco. The problem was that it submerged the Yosemite Valley, one of the most beautiful national parks in the USA.

Waterlogging and salinization

In the irrigation perimeters served by large dams, waterlogging and salinization may be serious problems. Waterlogging is the rise of the groundwater table to levels too close to the level of the land surface. In case of saturation of the root zone with water, plant growth is harmed. Another problem is that a high groundwater table will allow water to rise to the ground level by means of capillary suction. There, the water will evaporate and leave its salt content on the land surface. According to Varma (1999), waterlogging is caused inter alia by over-irrigation, seepage, lack of subsurface drainage, etc. Such land turns saline or alkaline and ultimately becomes unfit for cultivation. This is a serious

problem, since during the past two decades, the trend has been for the reduction of the acreage of irrigated land.

With a dam project for irrigation, there typically comes a grid of irrigation canals. Thus, one frequent reason for rising groundwater tables is that water is leaking from distribution canals into the groundwater.

Waterlogging could also be caused by irrigation per se, if more water is applied than can drain away from the soil. The poor infrastructure is part of the problem. Leaky irrigation canals can also contribute to waterlogging. Furthermore, alkalinization can clog the soil pores, making it difficult for the water to drain. To remedy the problem, one has to stop the seepage from canals by means of proper lining and maintenance. Furthermore, one should put a drainage system in place. This is, however, very costly. It may cost five times more than the other infrastructure that has gone into the project.

Waterborne diseases

A problem related to waterlogging is that dams and their distribution canals may give rise to pools of stagnant water. These pools have a tendency to serve as breeding grounds for vectors of waterborne diseases. This is a major problem in many developing countries.

Diseases spread by water related vectors are malaria, yellow fever, and dengue fever. While these diseases are not directly attributable to water quality, they are often spread by large-scale development of water systems that create conditions favorable to their hosts.

Water-based diseases come from hosts that either live in water or require water for part of their life cycle. These diseases are passed to humans when they are ingested or come into contact with the skin. The two most widespread examples in this category are schistosomiasis, which result from contact with snails that serve as hosts, and dracunculiasis (guinea worm), which results from ingesting contaminated host zooplankton (Gleick, 1998).

Conclusion

Dams are not inherently good or bad. Many dams have been very helpful in the development of the human endeavor. However, in far too many cases, shortsightedness and tunnel visions have resulted in dams, where the economic return has failed badly to make up for the adverse environmental and social impact of the dam.

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Cross-references

[Large Dams, Statistics and Critical Review](#)

LARGE DAMS, STATISTICS AND CRITICAL REVIEW

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Definition

According to the International Commission on Large Dams (ICOLD), a large dam is one whose height is:

- 15 m or higher
 - Between 10 and 15 m if it meets at least one of the following conditions:
 - A crest length of not less than 500 m
 - A spillway discharge potential of at least 2,000 m³/s
 - A reservoir volume 15,000,000 m³ or more
- (Source: McCully, 1996)

Development of large dams and reservoirs

Precipitation is not evenly distributed over a region in either density or seasonality. For more than 5,000 years

water-retaining structures have been built in different parts of the world to ensure that water is available for domestic and agricultural purposes throughout the year (Biswas and Tortajada, 2001). Some 6,000 years ago, the Mioris reservoir, with an area of 2,000 km² and a volume of 12 km³, was constructed in the Nile Valley. Herodotus regarded it as one of the Seven Wonders of the World (Avakyan and Ovchinnikova, 1971).

According to the ICOLD “World Dam Register 1988,” (ICOLD, 1988) there were 427 dams in the year 1900 but not more than 10 of them were large. During the twentieth century, there was a tremendous upsurge in the construction of large dams. Dams were built to provide water for irrigated agriculture, domestic or industrial use, to generate hydropower, or to help control floods. In industrialized countries, the construction of large dams tended to take place mostly in the first half of the twentieth century while most large dams in developing countries tend to have been constructed after 1950. The ICOLD report tells that there were some 5,200 large dams in service in the world by 1950. Now 60 years later there are more than 45,000 large dams. Sixty percent of all rivers have dams. Thirty to forty percent of irrigated agriculture gets its water from dams and some 20% of global electricity comes from dams.

In 1945, the USA had the five largest dams in the world: Hoover Dam on the Colorado River, Bonneville Dam on the Columbia River, Fort Peck on the Missouri River, Shasta on the Sacramento River, and Grand Coulee on the Columbia River. Currently, the highest dams and largest reservoirs tend to be located in developing countries or in the former Soviet Union. A list of the highest dams is provided in Table 1. Table 2 is a list of the largest reservoirs.

As a dam construction, the Tarbela Dam on the Indus River in Pakistan is the largest in the world. The construction is 2,743 m wide with a maximum height of 143 m. The total volume of earth and rock used for the project is 152.8 million cubic meters.

The main purpose of building very large dams is hydropower production. Dams with the largest hydropower potential are listed in Table 3. The Itaipu Dam is the largest operating hydroelectric facility in terms of annual generating capacity, which is 90–95 TWh, while the annual generating capacity of the Three Gorges Dam has been about 80 TWh in the last few years.

For a long time, construction of large dams was seen, in many places, as a prerequisite for economic development and increased well-being. In India, e.g., nothing signifies this belief more than the temples at the sources of “sacred fliers” being substituted by dams – the “temples of modern India” as Nehru called them. Thus, large dams have traditionally been developed in accordance with the prevailing development paradigm, i.e., a firm belief in the merits of industrialization and domination of Nature. The benefits of large dams in the early stages were relatively easy to quantify. Hydropower, irrigation, and flood storage were approached as primarily a mass balance analysis related to timing and delivery of water. The downside

Large Dams, Statistics and Critical Review, Table 1 The highest dams in the world (2010)

Dam	River	Country	Height (m)
Rogun	Vakhsh River	Tajikistan	335
Nurek	Vakhsh River	Tajikistan	300
Xiao wan	Lancang River	China	292
Grand Dixence	Grand Dixence	Switzerland	285
Inguri	Inguri River	Georgia, USA	272
Vaiont	Vaiont River	Italy	262
Manuel M. Torres	Grijalva River	Mexico	261
Tehri	Bhagirathi River	India	261
Alvaro Obregon	Mexique River	Mexico	260
Mauvoisin	Drance de Bagnes	Switzerland	250

Large Dams, Statistics and Critical Review, Table 3 Dams with the largest hydro-potential (2010)

Reservoir	River	Country	MW
Three Gorges	Yangtze	China	18,460
Itaipu	Parana	Brazil/Paraguay	14,750
Guri (Simon Bolivar)	Guri, Caroni	Venezuela	10,055
Tucurui	Tucurui	Brazil	8,370
Sayanao-Shushenskaya	Yenisei	Russia	6,500
Grand Coulee	Columbia	USA	6,495
Longtan	Hongshui	China	6,425
Krasnoyarsk	Yenisei	Russia	6,000
Bratsk	Angara/Yenisei	Russia	4,500
Ust-Ilmsk	Angara/Yenisei	Russia	3,920

Large Dams, Statistics and Critical Review, Table 2 The largest reservoirs in the world (2010)

Reservoir	River	Country	Volume (km ³)
Kariba	Zambezi	Zambia	180
Bratsk	Angara/Yenisei	Russia	169
Lake Nasser	The Nile	Egypt-Sudan	157
Lake Volta	Volta	Ghana	150
Manicougan	Manicougan	Canada	142
Lake Guri	Caroni	Venezuela	135
Williston Lake	Peace	Canada	74
Krasnoyarsk	Yenisei	Russia	73
Zeya	Zeya, Amur	Russia	68
Kuybushev	Volga	Russia	58

of these projects, when acknowledged, was approached from the perspective that any problem had an engineering “fix.” In hindsight, it is easy to critique this naïve approach of the original designs or approaches to resolve complex environmental issues.

From the 1930s to the 1970s, the construction of large dams became synonymous with development and economic progress. Viewed as symbols of modernization and humanity’s ability to harness nature, dam construction accelerated dramatically. This trend peaked in the 1970s, when on average two or three large dams were commissioned each day somewhere in the world. It was not until the late 1970s or 1980s that people started to appreciate the need for environmental and social impact assessments in the planning of large dam projects. By then, some 35,000 large dams had already been built. For many of these large dams the economic gains are dwarfed by the social and environmental costs. Past shortcomings and inequities remain unresolved, and experience with appeals, dispute resolution, and recourse mechanisms have been poor (World Commission on Dams, 2000). In industrialized countries, most of the criticism against large dams is related to the impacts on the aquatic ecosystem. In developing countries, however, social concerns tend to be more important. People have lost their land, their possibilities for flood-plain agriculture, or fishing opportunities due to dam constructions.

The most serious problem with large dams is the displacement of people. More than 45 million people have been displaced. The problem is worst in densely populated countries. It is estimated that some 35 million people have been displaced in India and some 10 million in China. Only the Three Gorges project has forced some 1.2 million people to move from their homes. In Scudder (2005) it is stated that living standard improvement occurred in only 3 cases out of 44 and were restored in only 5 cases.

Irrigation is a driving force behind the construction of many dams. In 1800, an estimated eight million hectares, an area about the size of Austria, were equipped with watering facilities. A number of large projects constructed during the nineteenth century, especially in India and what is now Pakistan, brought the total area irrigated to about 48 million hectares (Postel, 1993). As the world population has grown from 1.6 billion to 7 billion over a century, irrigation has become a cornerstone of global food security. The irrigated area nearly doubled in the first half of the nineteenth century. An even faster surge brought the total to more than 235 million hectares by the end of the century.

Irrigation projects generally endear themselves to agriculturalists because they tend to promote maximum yield per hectare. Also, irrigation projects have many attributes that satisfy the objectives of politicians, particularly a rapid, visible, and dramatic impact, and the tendency to be closely associated with a political promoter. Donors of foreign aid promote irrigation projects for similar reasons. However, lending for irrigation by the major international banks has declined after 1980, the main reason being that the costs of adding irrigation capacity – building new dams, reservoirs, canals, and distribution channels – have been rising in many countries, making it harder to justify such investments on economic grounds. Another reason is the poor performance and quality of many existing irrigation schemes. In many large surface water networks, less than half the water diverted from the reservoir actually benefits crops. Typical efficiencies for large projects in Asia run at about 30%. Much water seeps through unlined canals before it gets to the fields. An additional amount runs off the land or percolates

unused through the soil because farmers apply water unevenly, excessively, or at wrong times (Hjorth, 2001).

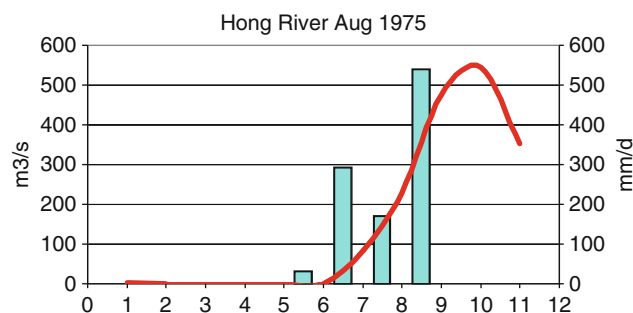
In Pakistan the World Bank has played a central role in the development of Pakistan's Indus Basin Irrigation System. Through the government's Revised Action Program (RAP) the emphasis shifted from development to improving system efficiency through rehabilitation and upgrading. An evaluation of the first four projects under the RAP strategy shows that although the water saved by these rehabilitation projects is little more than half of what was expected, this saved water is more than a new surface storage dam at Kalabagh would provide, and its unit cost is about one fifth of the expected unit cost of water from the Kalabagh Dam. The Kalabagh Dam Project was recently (2010) shelved because the four provinces of Pakistan were unable to reach an agreement on how the water from Kalabagh should be shared among them.

Dam failure

Dams may fail because of poor construction, poor management, or unexpected loads higher than those designed for. Some examples of dam break are given below.

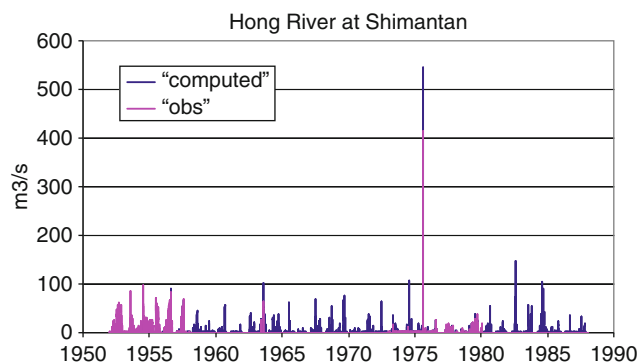
In 1950, the Chinese Government announced the "Harness the Huai River" project. The dual purpose of the program was to (1) control the river and prevent flooding and (2) utilize the water captured for irrigation and hydro-power production. Under this program, two major dams were built, the Banqiao Dam on the Ru River and Shimantan Dam on the Hong River. The Ru and Hong Rivers are not tributaries of the Huai River but are part of the same river system as the Huai River, i.e., the Huang He (Yellow River) system. There were numerous smaller dams built as well. The Banqiao Dam was designed to protect from a 1,000-year flood, which was estimated to be a 3-day storm of 530 mm. The Shimantan Dam was to protect from a 500-year flood, which was estimated to correspond to 480 mm of rain over a 3-day period. In the beginning of August 1975, there was a set of storms giving well over 1,000 mm as areal rainfall over 3 days. Point rainfall in an individual gauge was measured to 1,650 mm in the 3 days. The Banqiao and Shimantan Dam reservoirs were filled above capacity because the inflow by far exceeded the capacity of the outlet sluice gates. On August 8, the Shimantan Dam collapsed. The dam failure created a 6 m high and 12 km wide wall of water. Altogether, 62 dams collapsed and the flood spread over more than a million hectare of farmland throughout 29 counties and municipalities. At least 50,000 died and 11 million people in the region were affected. The observed precipitation and the observed-computed river flow in the Hong River are shown in Figure 1 (drawn from data from Bengtsson et al. (1995)). There were no river flow measurements after the collapse of the dams. Comparison with all previous and later river discharge is seen in Figure 2.

Another example is the Vaiont Dam in Italy. It is one of the tallest dams in the world; it is 262 m high, 27 m thick at the base, and 3.4 m at the top. It was overtopped in 1963. Warning signs of geological instability during the early stage of filling were disregarded, and the attempt to



Large Dams, Statistics and Critical Review,

Figure 1 Precipitation and river discharge August 1975 Hong River, Henan Province, China.



Large Dams, Statistics and Critical Review, Figure 2 River discharge Hong River, China. The observed flow was 400 m³/s prior to the collapse. The observations could not be continued but from hydrological modeling the peak after the dam break was estimated to 550 m³/s.

complete the filling led to a landslide, which created a gravity wave that brought massive flooding and destruction to the downstream Piave Valley, where several villages were wiped out. Some 2,000 people were killed. The dam structure was not damaged, but the dam reservoir has been kept empty since the accident.

The Teton Dam on the Teton River Canyon in Idaho, USA, failed during filling on June 5, 1976. The failure created a flood wave that killed 11 people and 17,000 head of cattle. Total damage estimates have ranged up to US \$2 billion. The dam was never rebuilt (Mark, 1993).

Review from the World Commission of Dams (WCD)

The Commission's two objectives with the review were:

- To investigate the effectiveness of large dams and assess alternatives for water resources and energy development
- To develop internationally acceptable criteria, guidelines, and standards for the planning, design, appraisal, construction, operation, monitoring and decommissioning of dams

Key recommendations in the WCD final report include the following:

- No dam should be built without the “demonstrable acceptance” of affected people, and without the free, prior, and informed consent of affected indigenous and tribal peoples.
- Comprehensive and participatory assessments of people’s water and energy needs, and different options for meeting these needs, should be developed before proceeding with any project.
- Priority should be given to maximizing the efficiency of existing water and energy systems before building any new projects.
- Periodic participatory reviews should be done for existing dams to assess such issues as dam safety, and possible decommissioning.
- Mechanisms should be developed to provide reparations, or retroactive compensation, for those who are suffering from existing dams, and to restore damaged ecosystems.

In assessing the large dams reviewed by the Commission it was found that:

- Large dams display a high degree of variability in delivering predicted water and electricity services – and related social benefits – with a considerable portion falling short of physical and economic targets, while others continue generating benefits after 30–40 years. Large dams have demonstrated a marked tendency toward schedule delays and significant cost overruns.
- Large dams designed to deliver irrigation services have typically fallen short of physical targets, did not recover their costs, and have been less profitable in economic terms than expected. Large hydropower dams tend to perform closer to, but still below, targets for power generation, and generally meet their financial targets but demonstrate variable economic performance relative to targets, with a number of notable under- and over-performers.
- Large dams generally have a range of extensive impacts on rivers, watersheds, and aquatic ecosystems, and in many cases have led to irreversible loss of species and ecosystems.

Historically, social and environmental impacts were left outside the assessment framework and the role of impact assessments in project selection remained marginal, even into the 1990s. Conflicts over dams have heightened.

Summary

The debate about dams is a debate about the very meaning, purpose, and pathways for achieving development. This suggests that decision-making on water and energy management should align itself with the emerging global commitment to sustainable human development and on the equitable distribution of costs and benefits. When the 45,000 large dams of today were assessed and

commissioned, environmental and social aspects were often neglected. Thus, there is a need to reassess old dams. The challenge is to more accurately define the economic, social, and environmental parameters in a basin context and develop a portfolio of appropriate response mechanisms. There is a need for genuine democracy including public participation and transparency in the development and implementation of energy and water policies.

Dams are neither inherently good nor inherently bad. They have been used to support the development models that prevailed at different times. An international overview of trends within the water sector shows that there is a remarkable communality in trends and patterns, i.e., intersectorial and interregional water allocation conflicts, concerning poor cost recovery and poor operational performance, and excessive government involvement and bureaucratic control. The use of water power and the development of irrigation schemes, both of which have a long, and most often, highly successful history, have to be approached anew. A subtle approach is needed, one that does not result in displaced populations, but one that does care for people, the environment, and marine food-chains.

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LAURENTIAN GREAT LAKES, INTERACTION OF COASTAL AND OFFSHORE WATERS

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Introduction

The Laurentian Great Lakes represent an extensive, interconnected aquatic system dominated by its coastal nature. While the lakes are large enough to be significantly influenced by the earth's rotation, they are at the same time closed basins to be strongly influenced by coastal processes (Csanady, 1984). Nowhere is an understanding of how physical, geological, chemical, and biological processes interact in a coastal system more important to a body of water than the Great Lakes. Several factors combine to create complex hydrodynamics in coastal systems, and the associated physical transport and dispersal processes of the resulting coastal flow field are equally complex. Physical transport processes are often the dominant factor in mediating geochemical and biological processes in the coastal environment. Thus, it is critically important to have a thorough understanding of the coastal physical processes responsible for the distribution of chemical and biological species in this zone. However, the coastal regions are not isolated but are coupled with mid-lake waters by exchanges involving transport of materials, momentum, and energy.

This review will focus on several mechanisms that contribute to the alongshore and cross-shore transport of material. These are (1) wave-driven processes, (2) coastal boundary layer processes including upwelling and downwelling flows, (3) episodic events such as storms, (4) the thermal bar, and (5) river plumes.

Subregions of the coastal zone

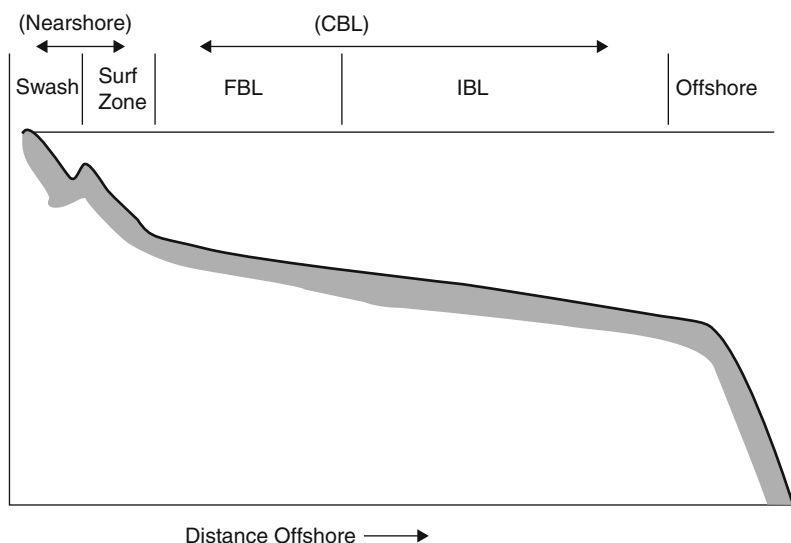
The first characteristic feature of coastal waters is their shallow depth, typically 0–20 m, compared with lake-average depths of 60–150 m except Lake Erie. The near-shore or coastal zone in the Great Lakes is defined as the zone that begins at the shoreline or the lakeward edge of coastal wetlands and extends offshore to the depth where the thermocline typically intersects with the lake bed in late summer or early fall (Rao and Schwab, 2007). This

delineation also includes the surf and swash zones in the littoral zone. Because of shallow depths in the coastal zone, currents near the bottom are often much larger than in deeper areas. Bottom friction plays a significant role in nearshore dynamics. The presence of the shoreline acts as a lateral constraint on water movements, tending to divert currents so that they flow nearly parallel to the shoreline. The shoreline also causes surface slopes to develop, which in turn affect water movements. The influx of freshwater runoff from the land affects the density of the coastal water. For a similar heat flux through the sea surface, the shallower water near the coast undergoes larger changes in temperature than deeper water. Because of these effects, coastal waters of the Great Lakes exhibit large horizontal gradients of density, often associated with changes in currents. The Great Lakes also undergo a complete cycle of isothermal to vertically stratified conditions in a year. The thermal structure in the Great Lakes generally depends on the season because of the large annual variation of surface heat fluxes (Boyce et al., 1989). During the unstratified period, storm action is the most important forcing, as higher wind speeds and the absence of stratification allow the wind forcing to penetrate deeper into the water column. In summer and fall most of the lakes are stratified with a distinct thermocline in the upper 20–30 m (Boyce et al., 1989).

Horizontal spatial scales of coastal physical processes can range from 10 m in nearshore areas for surface gravity waves to hundreds of kilometers for large-scale wind-driven flows. The flow regimes of the coastal zone are not all uniform from nearshore to offshore waters but vary appreciably as water depth changes. For convenience, the coastal zone can be divided into three regimes, namely, (1) the nearshore area consisting of swash and surf zones, (2) the frictional and inertial boundary layers, together known as coastal boundary layer (CBL), and (3) the open lake (Figure 1). In the open lake the momentum imparted by the wind stress is balanced by the Coriolis force, frictional forces are small, and wave-induced bottom agitation is minimal. In contrast, the frictional boundary layer (FBL) is dominated by bottom friction and lateral friction. At around 3 km from shore an outer boundary layer, known as the inertial boundary layer (IBL) develops due to the adjustment of inertial oscillations to shore-parallel flow (Rao and Murthy, 2001). Wave run-up and breaking waves are dominant sources of mean flows within the swash and surf zones.

Wave-driven processes

The wind excites surface waves that create hazardous conditions for recreation and navigation and are also the main cause for shoreline erosion. The most common wind directions over the Great Lakes region are south-westerly to westerly, but in a climate which is extremely variable from day to day, winds from other directions are quite



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 1 Schematic diagram of the subregions of the coastal zone (Source: Rao and Schwab, 2007).

frequent, and strong spells of easterly or north-easterly winds are not unusual. As wind-generated waves propagate from deeper water toward the shore, wave orbital motions must adjust to the shallower water depths, modifying the wave kinematics. Therefore, the greatest effect of wind waves occurs in the surf and swash zones. Inputs of storm runoff, combined sewer overflows, and streams occur in this zone. The swash zone with wave run-up and run-down on a beach forms the boundary between the surf zone and the backshore. It also determines the landward boundary of the area affected by the wave action. The surf zone is the area of water between the swash zone and the seaward side of breaking waves. The width of the surf zone is very small compared to the total width of the coastal boundary layer. In contrast to other regimes in the coastal zone, the surf zone is severely constrained laterally; therefore the geostrophic effects (steady currents sustained by a balance between the pressure gradient force and the Coriolis force) are negligible. Circulation is driven almost exclusively by forces resulting from the dissipation of breaking waves. The net onshore transport of water by wave action in the breaker zone, the lateral transport inside the breaker zone by longshore currents, and the seaward return of the flow through the surf zone by rip currents constitute a nearshore circulation system. Wave-generated currents, which transport beach material, are an important factor in the beach stability. The direction of littoral drift is determined by the angle of wave approach and associated longshore currents, and is particularly critical during periods of high lake levels. The predominant direction of the littoral drift depends on non-storm waves that contain much more total energy than is contained in storm waves of shorter duration. Wave-generated currents carry some

particles along the bottom as bed load, while other particles are carried some height above the bottom as suspended load.

The coastal boundary layer

The coastal boundary layer is the region between the wave-breaking zone and the open lake where frictional forces and the steering affect of the shore are dominant processes. The prime driving force of circulation in this zone is again the wind; however, the effects of stratification can become very important during the summer period. The wind action on coastal waters rapidly generates flow predominantly parallel to the coast. When a steady wind blows across a lake, the equilibrium condition of the water surface is a depression along the upwind end and an increase of elevation (storm surge) along the downwind end of the lake. Surface seiche, which is the oscillatory response of the lake surface after wind cessation, can also have a significant impact on the nearshore circulation in some of the Great Lakes. When a steady wind over the homogeneous lake pushes water downwind, the water level rises, and the resultant pressure gradient causes a return flow in the deeper parts of the lake forming two counter-rotating gyres.

Winds at mid-latitudes are usually quite variable, rarely displaying significant persistence for more than a day. Under these circumstances the transient properties of coastal currents are often of greater practical importance than the steady state for constant wind. These transient properties depend on the frequency of weather cycles. A particularly notable feature of coastal currents in the Great Lakes is the presence of inertial oscillations during the stratified period. At the latitude of the Great Lakes the inertial period is close to 17 h. Although these

oscillations are more like an organized flow, because of their oscillatory nature they can be viewed as large-scale fluctuations and as such contribute to dispersal processes in the coastal zone. In the coastal zone, these types of rotary motions are modified since the particle velocities perpendicular to the coast must vanish at the shoreline. Consequently, there is an adjustment zone, typically 5–10 km wide often referred to as the coastal boundary layer (Figure 2).

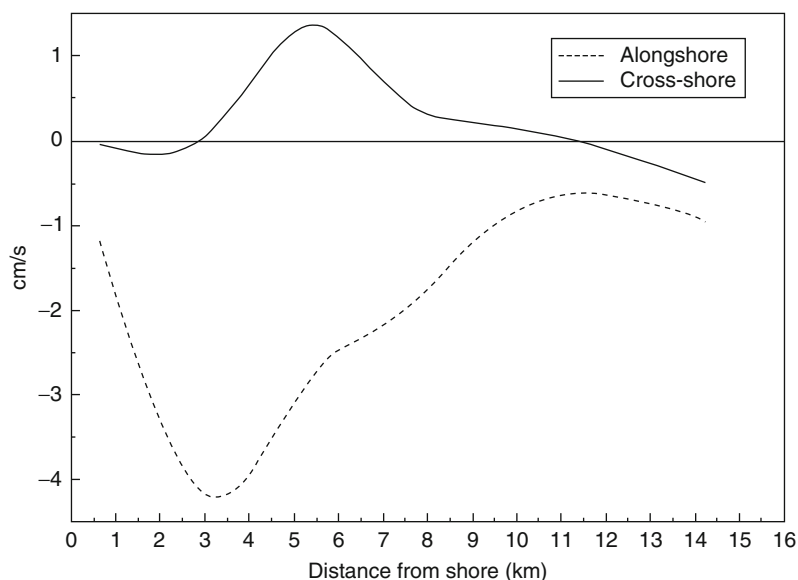
During the stratified season significant wind events cause upwelling and downwelling of the thermocline along the shore and within the CBL. If the coast is to the left of the prevailing winds, the wind-induced Ekman transport will be away from the coast in the surface layer and upwelling occurs near the coast. During this period an onshore and upslope transport occurs at some depth below the surface. On the other hand, if the coast is to the right of the wind, downwelling occurs. The transport in the surface layer is toward the coast, and offshore transport occurs below the surface layer. The changeovers from upwelling to downwelling regimes and vice versa are of particular interest to nearshore biology and chemistry studies. The offshore distance scale over which these events take place depends on the wind stress and near-shore bathymetry (Csanady, 1984) and is known as the Rossby radius of deformation (typically of the order of 3–5 km). In this zone a balance exists between wind stress, Coriolis force, and internal pressure gradient. A typical changeover from upwelling to downwelling is accompanied by marked changes in the thermal structure in this zone in a period of 4–5 days, exposing the zone to either epilimnetic water or hypolimnetic water depending upon the situation. Upwelling and downwelling have the

potential to produce large onshore-offshore transport of material.

During the stratified season in the Great Lakes two types of internal waves often occur after a strong wind event: Poincaré waves and internal Kelvin waves. Poincaré waves are the near-inertial period basin-wide oscillations of the thermocline characterized by anticyclonic phase propagation. These waves were first observed in the Great Lakes by analyzing temperature observations at municipal water intakes for cities around Lake Michigan (Mortimer, 1963). On the other hand, internal Kelvin waves are coastally trapped oscillations of the thermocline that progress cyclonically around the lake with a phase speed of 0.5 m/s (Beletsky et al., 1997). During periods of calm or weak meteorological conditions, coastal currents are usually weak. Experiments conducted on the Great Lakes showed that significant mass exchange between the CBL and offshore waters takes place during episodic events and the current reversals associated with the propagation of internal Kelvin waves. Complex patterns of cross-shore transport have been observed in upwelling systems including the Great Lakes.

Episodic events in Great Lakes

Circulation in the Great Lakes is also highly episodic with the most energetic currents and waves occurring during the strongest storms. During fall and winter seasons, the higher wind speeds and the absence of the thermocline allow the effects of wind action to penetrate deeper into the water column. In the Great Lakes, the gradients of many biogeochemically important materials are considerably higher in the offshore direction than in the alongshore direction. In the presence of these large gradients,



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 2 Mean alongshore and cross-shore components of currents (Source: Rao and Murthy, 2001).

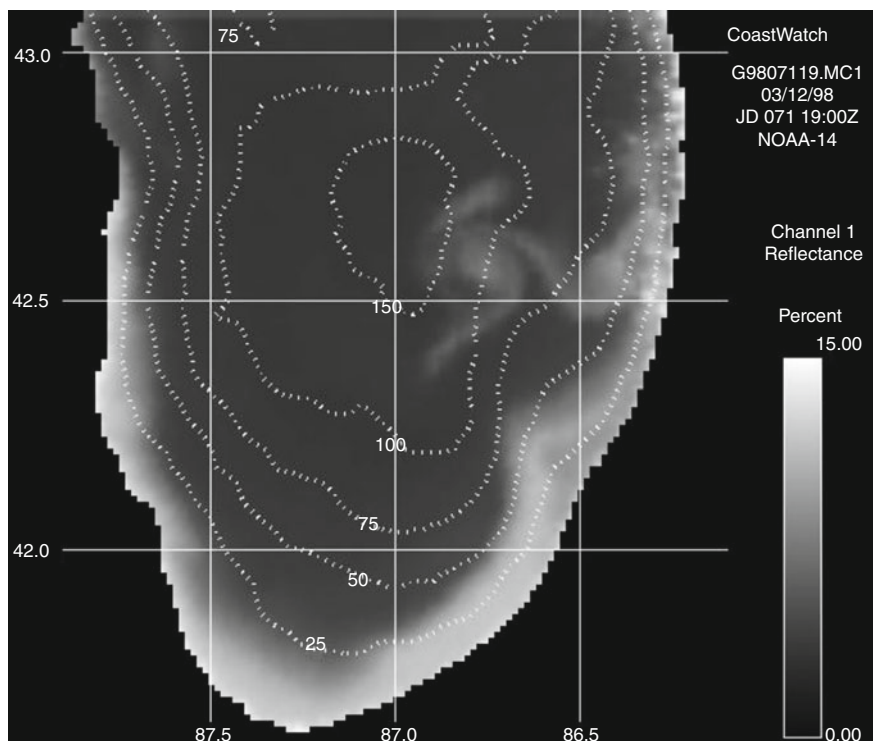
cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters. Spring and fall storms can create a nearshore zone of turbid water up to 10 km wide which sometimes encompasses a significant portion of the lake's coastal zone (Figure 3). Much of the resuspended material consists of fine-grained silty clay that can remain in suspension for several weeks after a storm. The total estimated amount of material resuspended during a large event can be comparable to the total annual load (erosion, atmospheric deposition, and tributary input) of fine-grained material to the entire basin.

In the case represented in Figure 3, it was observed that in the shallow waters of the southern basin of Lake Michigan, the water near the coasts moves in the direction of the wind toward the south, while return flow occurs in the deeper parts of the lake. This process forms two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left. These gyres are one of the important mechanisms for nearshore-offshore transport in the Great Lakes since they generate an area of intense offshore flow where they converge at the downward end of the lake. The mean and fluctuating coastal currents in southeastern Lake Michigan were studied during the winter and early spring during the three field years of the Episodic Events Great Lakes Experiment (EEGLE). The winter-spring currents in this region are quite depth-

independent, and the vortex mode identified earlier in offshore waters is also evident in the data from these coastal waters. The net seasonal currents during the winter season flow predominantly alongshore and toward the north. Time varying alongshore circulation is more closely tied to the alongshore component of the wind. The net offshore transport appears to be a result of the combination of wind-forced two-gyre circulation, Ekman veering of bottom boundary layer currents, and the topographic steering. However, the interannual variability of current speeds and magnitudes seems to be caused mainly by variability of surface wind forcing. The intermittent episodic circulation influenced by northerly storms causes significant asymmetry in the mean circulation pattern. There is also significant variability of circulation from one storm to another. The alongshore currents were initially driven by strong northerly wind pulses, but subsequently reverse direction as the forcing stops. The two-gyre circulation seems to be an important mechanism for the relaxation of currents as well as the offshore transport in the southern Lake Michigan. Direct wind-forced offshore transport was also observed in some regions.

The thermal bar

The thermal bar is a downwelling plume of freshwater at the temperature of maximum density (4°C), and is formed in temperate lakes in spring and fall when waters on either

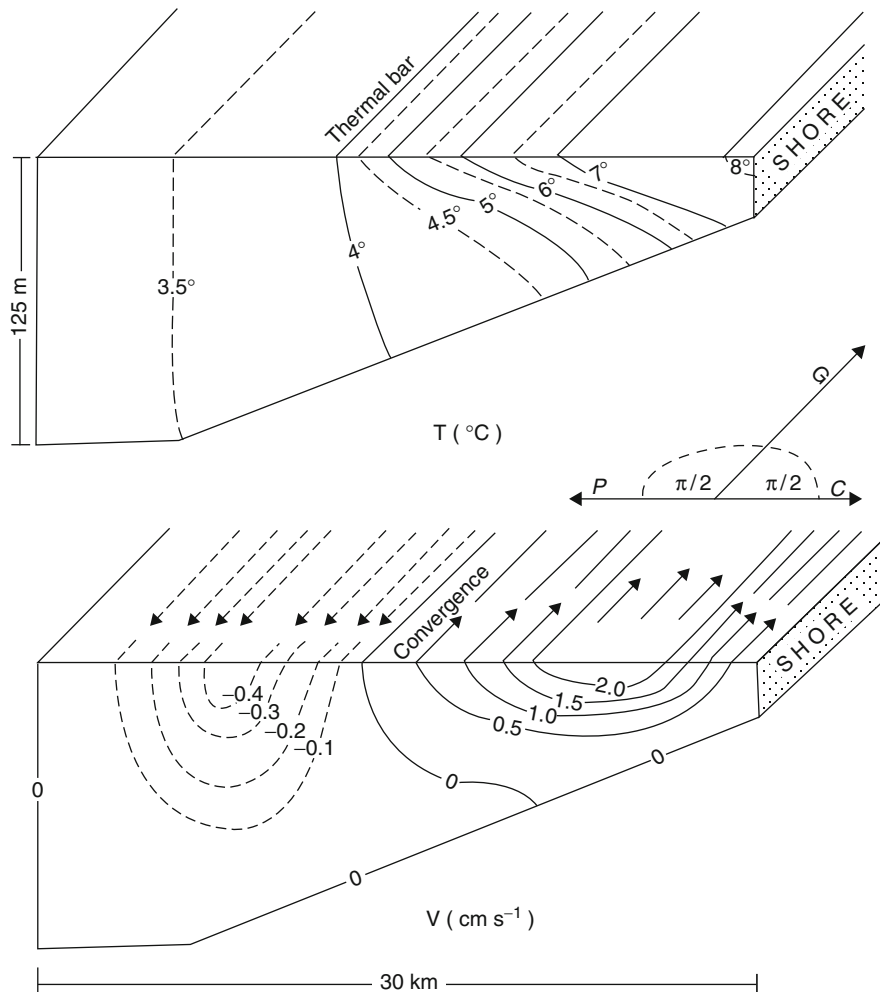


Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 3 Satellite picture showing reflectance during a winter storm in Lake Michigan.

side of the 4°C isotherm mix (Figure 4). The density-induced horizontal circulation in large temperate lakes of the northern hemisphere is counter-clockwise in the stably stratified nearshore region, and clockwise in the deep water region. The secondary circulation, perpendicular to the primary one, consists of two circulation cells, one on each side of the 4°C isotherm, where coastal and offshore waters mix and descend. This two-cell thermal bar circulation is important because of its role in inhibiting the horizontal exchange of water between the nearshore and offshore regions. The thermal bar can significantly affect the flow and thermal characteristics of the Great Lakes and may have significant influence on their ecological functioning. This effect is extremely important because a proper understanding of an ecosystem's interaction with the hydrodynamics is required to determine optimum nutrient loadings to the lake.

In the 2003 Lake Ontario experiment, the coastal circulation was mainly influenced by the alongshore winds.

One of the interesting observations in this experiment is that the thermal bar was stationary for several days. Although mean cross-shore flow decreased during the thermal bar period, the flow was depth-dependent. In general, theoretical models overestimated the progression rate of the thermal bar during the early phase. In the later phase, the models that incorporated the effect of horizontal heat flux in the thermal bar region were able to predict the significant increase in the progression rate. This study concluded that the effect of wind on the thermal bar seems to be an important feature and the models have to incorporate this effect. Also, the horizontal turbulent exchange parameters showed non-isotropic conditions in the shallow stably stratified region. The alongshore horizontal exchange coefficients were higher than cross-shore exchange coefficients. During the thermal bar period, the magnitude of both alongshore and cross-shore exchange coefficients decreased when the bar was in the nearshore zone and from mid-depth onward the thermal bar has not



Laurentian Great Lakes, Interaction of Coastal and Offshore Waters, Figure 4 Schematic diagram of the spring thermal bar (From Henderson-Sellers, 1984).

Water-quality analyses of the Niagara River have shown high concentrations of toxic chemicals that are introduced by the river plume into Lake Ontario. Much research has been conducted to investigate the dynamics of the Niagara River inflow into Lake Ontario. The near-shore thermal structure is altered significantly by the inflow, the warmer Niagara River plume extends beyond the river mouth in excess of 10 km, after which it eventually mixes with the ambient lake water. The vertical extent of the Niagara River plume can be 8–10 m, with the warmer inflowing water developing a frontal structure as it enters the lake. The gradient across the thermal front depends on the time of year and therefore on the difference between the temperature of the inflowing water and the ambient lake temperatures.

Prevailing wind conditions and lake circulation patterns determine the spread of the Niagara River plume in Lake Ontario. In most circumstances, a plume develops from the Niagara River mouth and tends to extend eastward along the south shore of the lake. In the initial phase, horizontal velocities from the Niagara River mouth are reduced significantly, and the river water is vertically well mixed over the shallow bar area. Beyond this initial phase, the river plume is deflected in response to lakewide circulation and the prevailing winds. In the transition phase, a large clockwise eddy between 10 and 12 km in diameter is formed to the east of the Niagara River mouth. The eddy appears often and lasts for a few days. From a water-quality standpoint, river outflow that is entrained into this zone of low net transport is effectively isolated from the mixing effects of the main shore-parallel currents. Consequently, this nearshore area can be a zone in which fine particulate material is deposited (Figure 5).

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LIGHT AND PRIMARY PRODUCTION IN LAKES

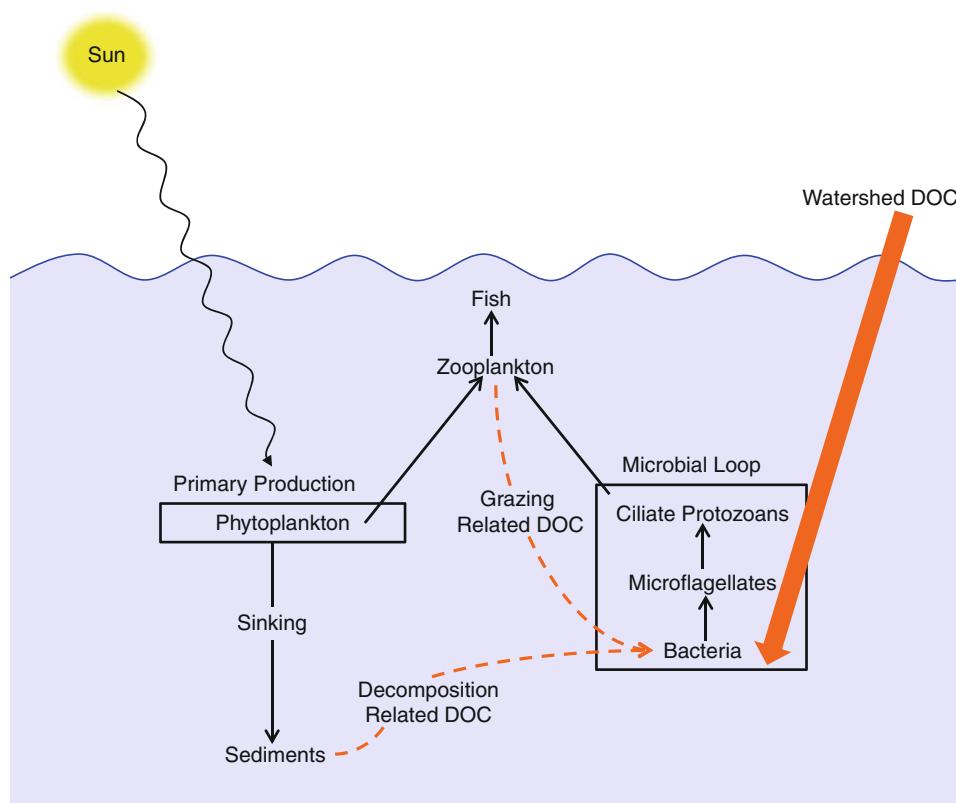
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Introduction

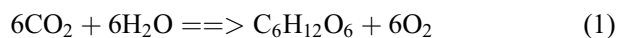
Photosynthesis is the primary source of energy that supports all aquatic life in the oceans, lakes, and reservoirs. It is of fundamental importance since it sets overall constraints on the flow of material and energy in aquatic ecosystems. Phytoplankton, through the process of photosynthesis, fix atmospheric carbon and become the base of the aquatic food web. Rates of photosynthesis are dependent on the intensity and spectral quality of light, which in the aquatic environment are in turn related to the optical characteristics of the water and depth, and the rate at which the phytoplankton circulate through the water column. This entry provides a brief overview of the factors influencing the underwater light climate and photosynthetic primary production, as well as some of the most common methodologies that have been widely employed to quantify rates of aquatic photosynthesis.

It is also important to acknowledge that over the last several decades it has become clear that in water bodies, which receive significant loads of dissolved organic carbon (DOC), the primary source of energy to the aquatic food web is this DOC being metabolized by aquatic bacteria. This “microbial loop” (Tranvik, 1992) is common in lakes with forested watersheds such as those found across the boreal region, where the DOC inputs supporting the aquatic food web may in fact be largely the result of terrestrial photosynthesis in the forested watersheds surrounding the lakes (Figure 1). In other cases, such as clear water lakes or the oceans, inputs of DOC are of lesser importance, and aquatic food webs will be supported to a much greater extent by phytoplankton photosynthesis.

The basic chemical equation describing photosynthesis (Equation 1) describes the process by which carbon dioxide and water are transformed by photosynthesis into carbohydrates (also referred to as sugars or photosynthate).



Light and Primary Production in Lakes, Figure 1 Simplified diagram showing the relative roles of primary production and microbial processes in supporting the aquatic food chain. The importance of the microbial loop is greatly enhanced by external loading of DOC.



Measurement of aquatic photosynthesis is based on either quantifying the removal of carbon dioxide (CO_2) from the water, or the evolution of oxygen from the photosynthesizing phytoplankton. Oxygen evolution by the phytoplankton is balanced by respiration (R), which using the stored photosynthate, removes dissolved oxygen (DO) from the water and releases CO_2 back into the water.

Measurements of primary production can account for both photosynthesis and respiration. Gross primary production (GPP) is the total carbon uptake by the phytoplankton, whereas Net Primary Production (NPP) is $\text{GPP} - \text{R}$ or the difference between carbon uptake due to photosynthesis and carbon loss due to respiration. When using these terms the context of scale is of importance. Measurements made on a incubated sample over a short time interval will tend to represent processes occurring in an isolated part of the water body from which the sample was obtained. For example, an incubation that measures the uptake of carbon over relatively short time-scales where R does not significantly reduce the recently acquired carbon are often considered GPP. Net Ecosystem Production (NEP), although calculated in the same way

($\text{GPP} - \text{R}$), differs from NPP in that NEP accounts for GPP and R in the entire aquatic ecosystem. While in theory estimates of GPP and R made from isolated samples could be scaled up to give ecosystem values, NEP is usually based on measurement methodologies that attempt to account for system-wide changes in CO_2 or O_2 .

Underwater light

Primary production is of course a function of light or more precisely the photon flux density that can be absorbed by the phytoplankton photosynthetic pigments. It is therefore, both the intensity and spectral composition of the light that influences the rate of photosynthesis. In practice, when estimating primary production, the preferred measure of light is photosynthetically active radiation (PAR).

$$\text{PAR} = \int_{700}^{400} E_d(\lambda) d\lambda \quad (2)$$

where PAR is the integral photon flux between 400 and 700 nm measured as $\mu\text{moles m}^{-2} \text{s}^{-1}$ (also referred to as $\mu\text{E m}^{-2} \text{s}^{-1}$), and E_d is downwelling photon irradiance at wavelength (λ).

PAR is attenuated with depth as a consequence of both absorption and scattering of photons as they pass through the water, and this rate of attenuation can be described by Equation 3

$$E_d = E_0 e^{-K_d \cdot z} \quad (3)$$

where E_d is the downwelling irradiance at depth z and E_0 the downwelling irradiance just below the surface (depth 0). E_d can be either wavelength specific or integrated over the PAR wavelengths. K_d is the diffuse attenuation coefficient of downwelling irradiance, which can in turn be calculated from a profile of underwater irradiance measurements. Commercial instruments are available that measure underwater light both spectrally, or more commonly as a single irradiance over the PAR bandwidth. K_d (m^{-1}) is equal to the slope of the relationship of the natural log of irradiance versus depth. K_d can be related to the coefficients of absorption scattering using an approximate relationship (Kirk, 1981)

$$K_d(\lambda) = \sqrt{a(\lambda)^2 + 0.256a(\lambda)b(\lambda)} \quad (4)$$

where a and b are the coefficients of absorption and scattering (m^{-1}). Similar relationships which explicitly account for the variation in solar angle and the three-dimensional scattering characteristics of the water (volume scattering function) are also available (Kirk, 1994).

As can be seen from Equation 4, in all but the most turbid waters, the greatest effect on attenuation occurs through absorption. Scattering in the upward direction (backscattering) will directly affect attenuation, while forward scattering will also increase attenuation by increasing the path length that a photon takes to reach a depth and therefore the probability of absorption. It is because of the effects of scattering that K_d is most correctly referred to as the *diffuse* attenuation coefficient.

The attenuation coefficients of different waters, and therefore the light available to support photosynthesis in different waters will be dependent on the concentrations of absorbing compounds or optically active substances in the water, namely, the concentrations of phytoplankton, colored dissolved organic matter (CDOM), and detrital particulate matter, as well as the absorption of pure water itself (Figure 2).

It is the concentration and interaction of these absorbing compounds that influence the attenuation of PAR and the spectral quality of PAR in different water bodies. From Figure 3, which shows the spectral composition of irradiance in the Swedish great lakes, the importance of variations in the concentrations of optically active substances, particularly CDOM (Figure 2b), becomes apparent. Increasing CDOM absorption in the blue to green wavelengths (400–550 nm) greatly influences the magnitude and spectral shape of the subsurface irradiance spectra. Not only is PAR attenuated more rapidly in the more

colored waters, a much greater proportion of PAR occurs in the longer wavelengths in these waters. This results in the light affecting photosynthesis mostly occurring in the red phytoplankton absorption peak (~660–670 nm, Figure 2c) in the more colored waters, while in clearer Lake Vättern the broader blue (~400–500 nm) phytoplankton absorption is also of importance in influencing photosynthesis.

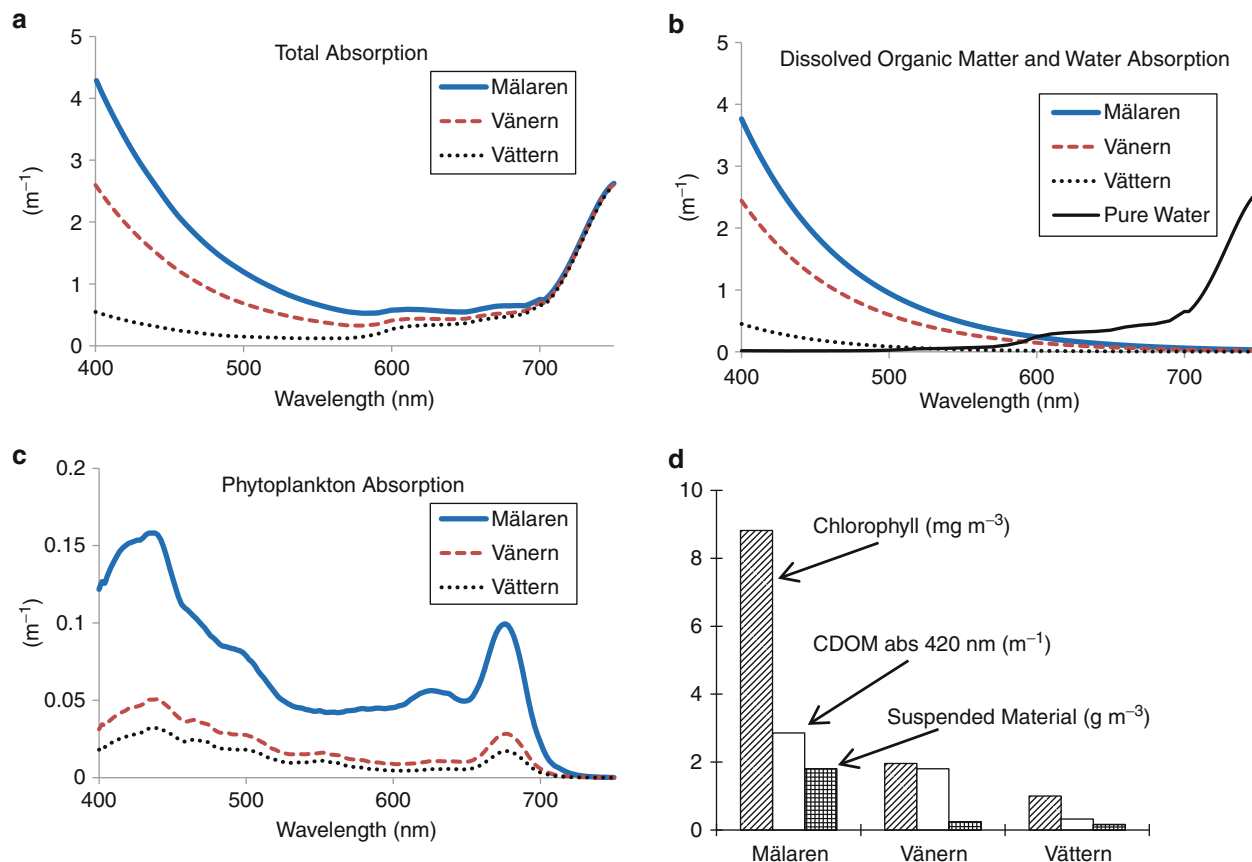
A more precise definition of light in relation to photosynthesis was defined by (Morel, 1978) that accounts for spectral variations in irradiance and phytoplankton absorption. Photosynthetically useable radiation (PUR) is calculated as the integral of the product of the underwater light spectra and the spectral phytoplankton absorption coefficient. While this, as the name suggests, provides a much more accurate estimate of the available light that could drive photosynthesis, it is not as widely used as PAR due the added requirement to measure spectral irradiance and phytoplankton absorption.

Measurement of primary production

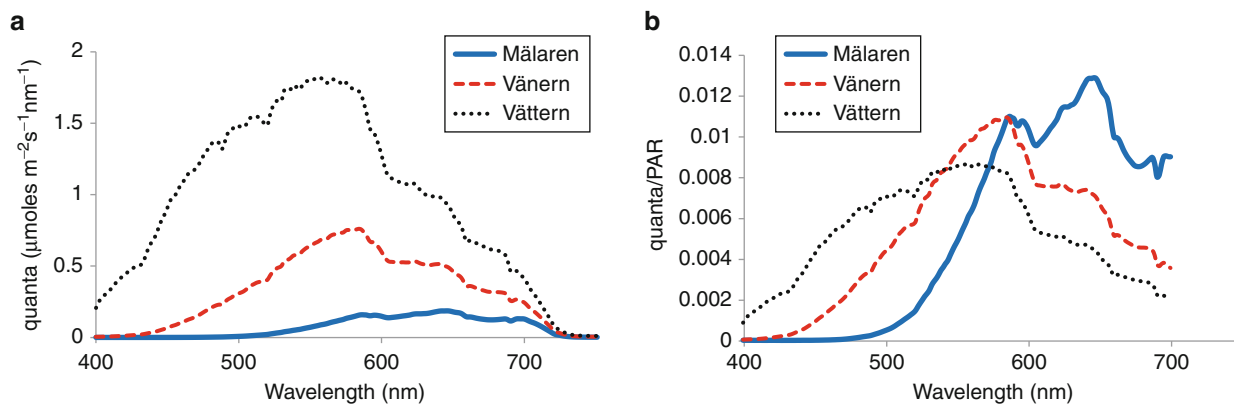
Some of the first estimates of aquatic primary production were made using chemical estimates of changes in DO concentration (Odum, 1956). Increases in DO concentration when phytoplankton are exposed to light are a measure of NPP under illuminated conditions, whereas depletion of DO in the dark is a measure of R. Both illuminated and dark measurements are often combined to calculate GPP, R, and NPP. The advantage of this method is that it is simple to use and based on a relatively common chemical water quality test that is well described and easily used. The disadvantage is that the precision of the method was not so high as to allow for rapid assessments or measurement in low productivity systems.

In the 1950s, use of the radioisotope ^{14}C was introduced as a means of sensitively estimating the uptake of carbon by phytoplankton (Steemann-Nielsen, 1952; Rodhe, 1958). When added to water as bicarbonate ($H^{14}CO_3$) the radiolabeled carbon equilibrates with dissolved CO_2 and is taken up by photosynthesis and incorporated into cellular carbohydrates. If the phytoplankton are then collected, the incorporated ^{14}C can be sensitively estimated by liquid scintillation counting, and from knowledge of the ratio of ^{14}C to total dissolved inorganic carbon in the incubated sample, total carbon uptake can be estimated. The advantages of this method is that it is much more sensitive than DO methods allowing accurate measurements in low productivity water bodies, as well as short-term measurements which reduce the containment affects associated with incubation. The disadvantage of the ^{14}C method is that it does involve radioactive substances which require a greater level of care and skill in handling. Unlike the oxygen, method ^{14}C estimates of productivity do not give estimates of R, but instead give an approximate estimate of GPP.

When photosynthesis is estimated by measuring the rate of carbon uptake or DO evolution three basic measurement strategies are generally used: (1) incubation of samples in the lake at the in situ conditions from where



Light and Primary Production in Lakes, Figure 2 Spectral variations in the absorption of water from Sweden's three largest lakes: Mälaren, Vänern, and Vättern. (a) Variation in total absorption spectra between lakes. (b) Variation in CDOM absorption between lakes and the absorption spectra of pure water. It is the combined effects of water and CDOM that most strongly affect the total absorption characteristics of the lakes. (c) Variations in phytoplankton absorption between lakes. These spectra were simulated using the methods described by Pierson and Strömbeck (2000) based on the median concentrations of optically active substances (d) that can be estimated from long-term monitoring data.



Light and Primary Production in Lakes, Figure 3 (a) Spectral variations in subsurface irradiance in lakes Mälaren, Vänern, and Vättern. All measurements were made at the 3 m depth at midday under clear sky conditions. (b) Differences in the spectral shape of the subsurface irradiance are enhanced by normalizing the irradiance at each wavelength by the integral PAR irradiance associated with that spectra.

the samples were obtained, (2) short-term incubation in the laboratory, and (3) monitoring of diel variations in free water DO using electrochemical sensors.

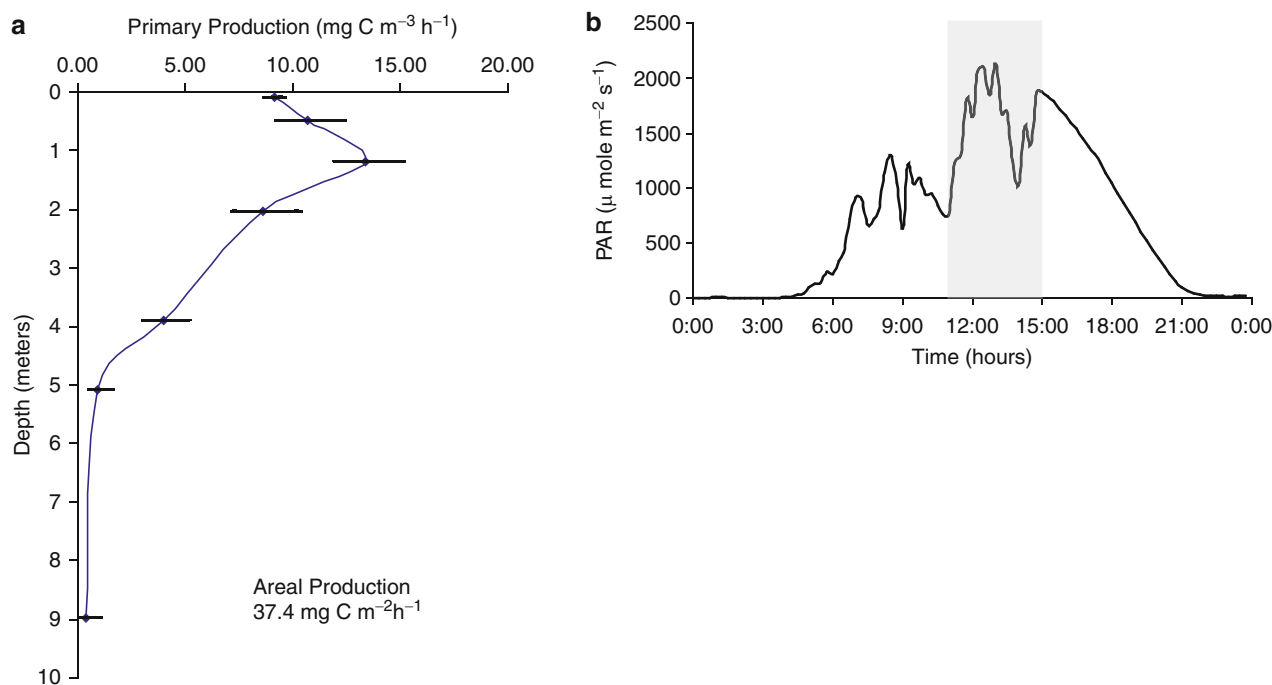
In situ incubation

Measurements of primary production can be estimated from the changes in the concentrations of either DO or ^{14}C in samples incubated over a given time interval. One way to accomplish this is to incubate the samples under the same conditions from where they were collected. This is commonly referred to as in situ incubation. Water is collected from a number of depths within the euphotic zone (between the surface and the depth of 1% PAR attenuation), the initial concentration at each depth is measured, the samples are placed in clear (light) and dark (0 light transmission) bottles and resuspended at the depth and ambient conditions from which the samples were obtained. After a given time (often 4 h) the bottles are retrieved, the sample fixed to stop further biological activity, and the concentrations measured. When measuring oxygen, increases in light bottle DO can be used as an estimate of NPP over the time of incubation, whereas reductions of DO in the dark bottles give an estimation of R. GPP can be calculated as the sum of NPP from the light bottle and R from the dark bottle. When measuring ^{14}C uptake, increases in algal ^{14}C over the time of the incubation is an approximate measurement of GPP

since it is assumed that equilibrium between the cellular concentrations of labeled and non-labeled carbohydrates is not complete, and that the alga respiration of ^{14}C is not in proportion to the true rate of respiration. Dark bottle changes in ^{14}C are therefore small and only used as a background correction.

Some measurement of algal biomass (often chlorophyll) is usually made at each depth so that the production rates can be normalized to biomass. Measurements at the different depths can be integrated vertically to give areal rates of production (Figure 4).

The disadvantage to in situ incubation is that the phytoplankton may not in fact be exposed to the true conditions that they would actually experience in the lake, if the water is circulating within the euphotic zone. The phytoplankton may adapt to the light conditions in the incubation bottles (photoadaptation), and these light levels may differ in both intensity and spectral quality from the light that would on average be experienced by phytoplankton freely circulating through the water column. As a result of such differences in light exposure the production estimated from the incubation can be different from true in situ levels. A related problem is that samples exposed at shallow depths may receive artificially high levels of light exposure sufficient to reduce levels of photosynthesis as a result of photoinhibition, and this will again lead to errors in estimating true levels of production.



Light and Primary Production in Lakes, Figure 4 Primary production measured using ^{14}C incubation method Lake Erken, Sweden (Pierson Unpublished). (a) Vertical profile of estimated rates of carbon uptake line is mean of two replicate measurements at each depth. Lower productivity in surface bottles is likely due to containment effects. (b) Surface PAR irradiance on day of experiment. Shaded section corresponds to the time of the experiment.

Modeling: use of the PI relationship

Data obtained from in situ incubations can be integrated over the depths of measurements to give an estimate of water column productivity over the course of the incubation (Figure 4). However, to estimate productivity over longer timescales, simply extrapolating through time between separate in situ estimates of productivity will be subject to error as a result of variations in light intensity over diurnal to seasonal timescales, and to a lesser extent changes in water transparency (K_d Equation 3). A better method to estimate daily-seasonal variations in primary productivity is to use the incubation to measure the relationship between light intensity and primary production and to parameterize these data into an equation that predicts primary production as a function of light intensity. The relationship between light intensity and primary production is commonly referred to the photosynthesis–light or production–irradiance (PI) relationship. Common equations describing the PI relationship are given by Jassby and Platt (1976) and they recommend Equation 5

$$P^B(I) = P_{\max}^B \tan h\left(\alpha^B \frac{I}{P_{\max}^B}\right) + R^B \quad (5)$$

where $P^B(I)$ is photosynthetic rate normalized to phytoplankton biomass (chlorophyll) ($\text{mgC mgChl}^{-1} \text{h}^{-1}$) at a given PAR irradiance ($\mu\text{mole m}^{-2} \text{s}^{-1}$), $P_{\max}^B$ is the light saturated maximum level of photosynthesis ($\text{mgC mgChl}^{-1} \text{h}^{-1}$), α^B is the slope of the initial light limited portion of the PI curve ($\text{mgC mgChl}^{-1} \text{h}^{-1} [\mu\text{mole m}^{-2} \text{s}^{-1}]^{-1}$), and R is any increase in carbon due to respiration ($\text{mgC mgChl}^{-1} \text{h}^{-1}$).

Seasonal estimates of primary production can then be estimated from measurements of surface PAR irradiance which when input to Equation 3 can be used to predict the temporal variations in light with depth. Combining the predicted light with the PI relationship (Equation 5) allows estimates of primary production to be integrated both over depth and through time. Modeled variations in primary productions therefore depend on measured variations in surface PAR irradiance, and an assumption that phytoplankton biomass, K_d and the PI parameters $P_{\max}^B$ and α^B remain relatively constant. While in reality none of these are constant, they are not as temporally variable as surface irradiance, and assuming constant values allows estimations of areal primary production that do account for short-term variations in light intensity (Pierson, 1989). Errors can be reduced by regular sampling to account for variability in the fixed parameters.

While in theory it is possible to estimate the PI relationship from in situ incubations, this is difficult since sky conditions are rarely cloud-free during the entire incubation (Figure 4b), and therefore, the full range of light intensity that could be experienced by the phytoplankton over longer time intervals are rarely measured during the incubation period. There are also a limited number of light levels that can be measured by the in situ technique due to sample processing time and practical limitations on

the number of samples that can be suspended throughout the euphotic zone. Lewis and Smith (1983) introduced a rapid ^{14}C incubation method that overcame many of these problems. The “photosynthetron” incubator was deployed either in the laboratory or on ship, and consisted of manifold that held 25–50 scintillation vials over a strong light source. Between the light and the individual vials were differing levels of neutral density filters, so that the PAR exposure in the vials covered the full range that could be expected in the natural environment (approximately, $0\text{--}2,000 \mu\text{moles m}^{-2}\text{s}^{-1}$). A water sample was strongly enriched with ^{14}C and rapidly dispensed into all vials. The vials were cooled to in situ water temperature, and were illuminated for 20–30 min. At the end of the incubation, the samples are fixed to prevent further photosynthesis, and the excess inorganic ^{14}C in the sample is removed by acidification, before the organically bound ^{14}C was measured by liquid scintillation counting.

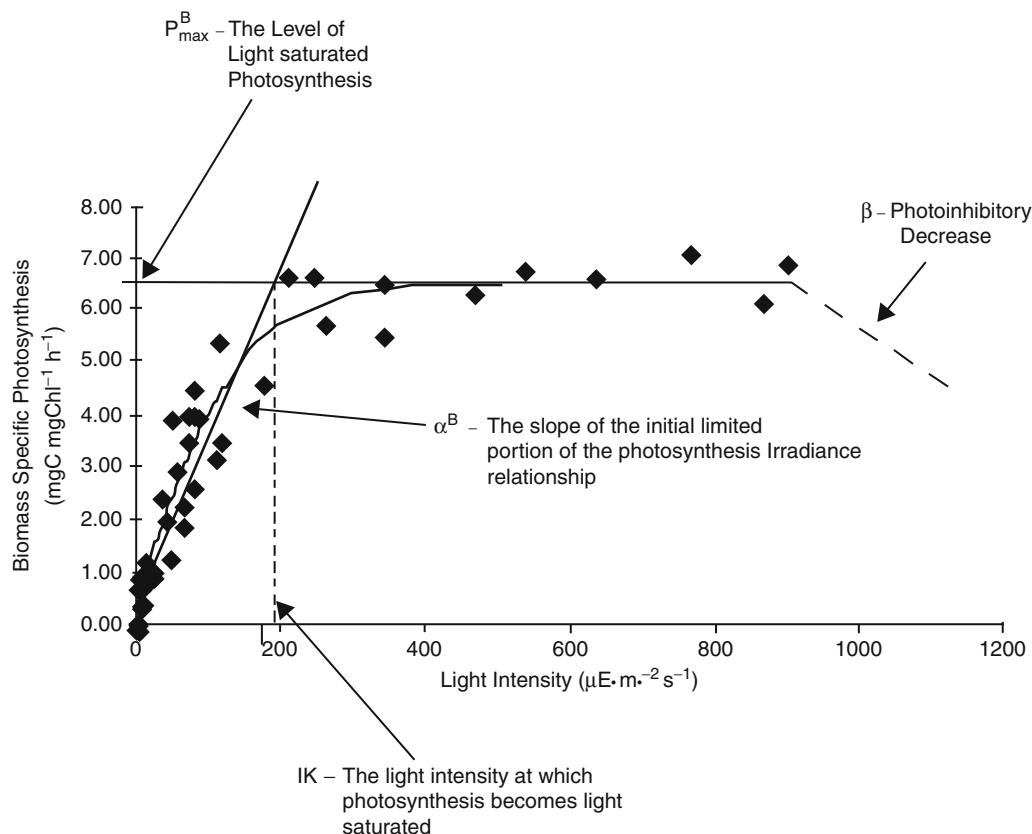
The advantages of this method are that photosynthesis is measured over a large range of light intensity, ensuring the PI relationship is well represented (Figure 5), and that confident estimates of α and $P_{\max}$ can be made for further modeling of lake system productivity. The short incubation time also minimizes adaption of the phytoplankton to the incubation light intensity so that the PI relationship obtained should be more reflective of phytoplankton light adaptation to true in situ light levels. Consequently, this method also provides a means to monitor changes in the PI relationship over time and space.

The main disadvantage of this method is that the incubation should be done on ship or at laboratory close to the water body, so that the phytoplankton do not acclimatize to the low light in the sample bottle. The second disadvantage is that the spectral quality of the PAR in an incubator illuminated by an artificial light source will not be the same as the spectral quality in situ. This can lead to some error in the estimates of the true in situ PI relationship.

Free water monitoring

A final means of estimating lake primary production and metabolism is by monitoring the free water concentration of DO using oxygen sensors suspended in the lake mixed layer. In situ changes in DO are estimates of NEP since they include the net effect of photosynthesis and respiration in the water volume measured. Furthermore, night time changes in DO can be assumed to be a result of R alone. This method has become more practical with the advent of optically based oxygen sensors that show lower levels of drift and require less frequent calibration, and the availability of low cost and reliable data loggers that allow reliable recording of high-frequency data. Often the sensor and data logger are combined into a single sonde system that can be moored unattended at depth, and retrieved periodically for data collection and sensor calibration.

Free water methods for estimating GPP, R , and NEP are reviewed by (Staehr et al., 2010). From frequent measurements (hourly or less) of DO, estimates of NEP are



Light and Primary Production in Lakes, Figure 5 An example of the relationship between biomass-specific photosynthesis and PAR irradiance measured in a laboratory incubator using ^{14}C . Photosynthesis initially increases linearly with irradiance at a slope of α^B . At an irradiance of IK photosynthesis reaches the light-saturated rate of $P_{\max}^B$. At even higher irradiances a decline in photosynthesis with a slope of β may occur due to photoinhibition (from Pierson, 1989, 1990).

calculated. Interval estimates of NEP can be extrapolated over the day (light period), and overnight to get estimates of R . If the assumption is made that the rate of R derived from night time measurements is also that occurring during the day, GPP can be estimated as the sum of the rates of NEP estimated during daytime, and R estimated during the night. Complicating this method are the need to account for the transfer of oxygen across the air–water interface (Gelda and Effler, 2002a) and the advection of DO in and out of the water volume measured by the sensor (Hanson et al., 2008), and spatial variability in primary production (Van de Bogert et al., 2007). The advantage of free water methods are that there will be no errors associated with incorrect experimental light exposure due to artificial containment, or a spectral mismatch between the incubator and in situ light. Furthermore, at least if the lake is well mixed, this method should potentially give a good estimate of the true NEP in the mixed layer, and avoid many of the pitfalls associated with scaling up small contained incubations to large lake volumes. (Gelda and Effler, 2002b) have successfully deployed oxygen sondes on profiling lake monitoring buoys and have developed enhanced methods for estimating NEP using vertical

profiles of dissolved oxygen concentration in order to better estimate in situ productivity throughout the entire water column. Despite the complications and assumptions associated with free water estimates of primary production, the method has gained wide acceptance and is becoming widely used to estimate lake GPP, R , and NEP. The lack of the containment affects, and power of collecting data over long time periods at high-sampling frequency has made free water methods very attractive.

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LIMNOLOGICAL STUDIES IN LAKE ERKEN SWEDEN

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Introduction

Limnology in Uppsala has its roots in the research fields of freshwater botany and zoology. The studies of Gunnar

Lohammar on water chemistry and higher vegetation in Swedish lakes, the classic study by Wilhelm Rodhe on environmental requirements of freshwater algae, and the comprehensive zoological studies of Sven Ekman created the scientific basis of limnology at Uppsala University.

In 1928 Carl Malmén donated the Norr Malma farm to Uppsala University and established the foundation for investigation of Lake Erken and especially the conditions for its crayfish (*Astacus astacus*) population. Based on the donation, a decision was taken in 1944 to establish a limnological research laboratory including space for accommodation. The first step was to renovate an old cottage on the shoreline of the lake. In the summer of 1946, the laboratory had finally been equipped for limnological studies and the work to understand the ecological structure and function of Lake Erken (Figures 1 and 2) could start under the leadership of Wilhelm Rodhe (1946).

The Erken Laboratory of today was built 1950–1951 with support from Knut and the Alice Wallenberg foundation and renovated and enlarged in 1994. The manor building of the farm was turned into a building for lodging of students in 1951.

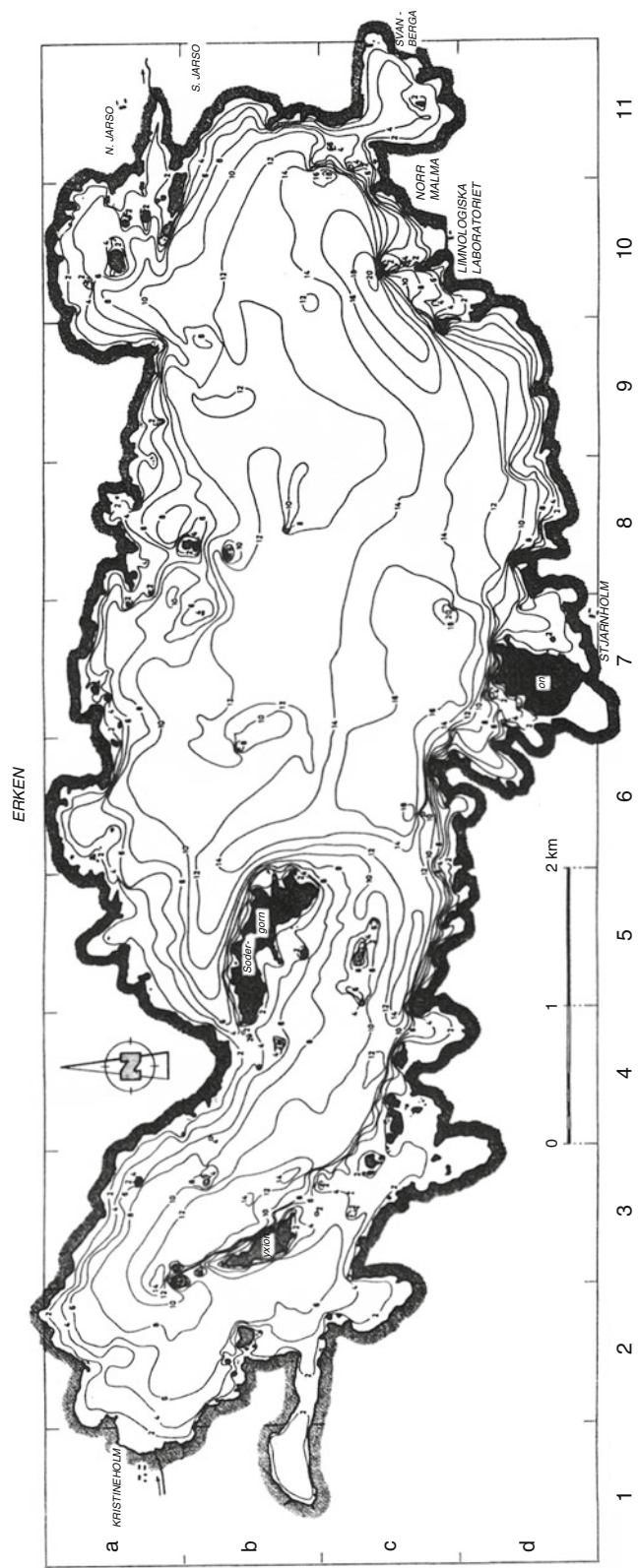
For more than 65 years, limnological courses and limnological research has been performed at the station with increasing intensity. Today the permanent staff is around 10 people and the analytical laboratory is certified by Swedac and limnological insights are given to more than 1,700 pupils and students yearly. The lake and its inlets are monitored on a weekly and monthly basis. A program that has run from the late 1980s to date, was based on fundamental water quality parameters. To describe the limnological studies performed in Lake Erken is an almost impossible task and I will only highlight a few examples from each decade.

The investigations of Lake Erken started already in the 1930s by Gunnar Lohammar, and Heinrich Skuja studied the phytoplankton species composition in the 1940s.

In the 1950s, Wilhelm Rodhe, Richard Vollenweider, and Arnold Nauwerck performed the first in situ measurements of phytoplankton production in lakes using the C^{14} technique (Rodhe et al., 1958). Arnold Nauwerck (1963) defended his thesis “Die Beziehungen zwischen Zooplankton und Phytoplankton im See Erken.” This was a pioneering work and the first thesis to be defended at the Department of Limnology at Uppsala University.

Wright and Hobbie published “Use of glucose and acetate by bacteria and algae in aquatic studies” in Ecology after experiments performed in Lake Erken (Wright and Hobbie, 1966). Roland Pechlaner studied the spring development of phytoplankton in the late 1960s (Pechlaner, 1970).

Ulf Granhall and Alf Lundgren continued the tradition of in situ experiments by measuring nitrogen fixation in Lake Erken (Granhall and Lundgren, 1972). Bengt Boström and Kurt Pettersson studied the spring development of phytoplankton again (Boström and Pettersson, 1977) and Kurt Pettersson defended his thesis “Orthophosphate, alkaline phosphatase activity and algal surplus phosphorus in Lake Erken” (Pettersson, 1979).



Limnological Studies in Lake Erken Sweden, Figure 1 Bathymetric map of Lake Erken, area 25 km², average depth 9 m, maximum depth 21 m.



Limnological Studies in Lake Erken Sweden, Figure 2 View of Lake Erken from the Erken Laboratory.

In the 1980s, Russel Bell followed up on the tradition of bacterioplankton studies with his thymidine incorporation measurements combined with estimations of bacterioplankton dynamics (Bell, 1984). Torbjörn Tirén and Bengt Boström followed nitrification and denitrification in lake sediments (Tirén and Boström, 1985). Richard Johnson defended his thesis “Life histories and coexistence of *Chironomus plumosus* (L.), *C. anthracinus* Zett (Diptera: Chironomidae) and *Pontoporeia affinis* Lindström (Crustacea: Amphipoda) in mesotrophic Lake Erken” (Johnson, 1986). Don Pierson made extensive measurements of primary production of phytoplankton in Lake Erken resulting in the thesis “Effects of vertical mixing on phytoplankton photosynthesis and phosphorus deficiency” (Pierson, 1990).

In the 1990s, the studies in Lake Erken increased dramatically with more than 60 publications in refereed journals. The research group lead by Kurt Pettersson, Vera Istvanovics, and Don Pierson followed the phosphorus turnover in the lake and the phytoplankton development with focus on the summertime and the cyanobacteria *Gloeotrichia echinulata* (Istvanovics et al., 1993; Pettersson et al., 1993). Russel Bell and colleagues continued their work on bacterioplankton and Katarina Vrede presented her thesis “Bacterioplankton Production and Biomass in Two Lakes of Different Trophic Status” (Vrede, 1997). Willem Goedkoop and Erik Törnblom studied the pelagic-benthic coupling (Goedkoop and Törnblom, 1996) and Gesa Weyhenmeyer investigated the sedimentation and resuspension of particles (Weyhenmeyer, 1996). Maria Kahlert focused on benthic algae and their phosphorus status and summarized her results in the thesis “Biomass and Nutrient Status of Benthic Algae in Lakes” (2001). Also dinoflagellates were studied intensively and Karin Rengefors finalized her thesis “The role of resting cysts in the Survival and Succession of Freshwater Dinoflagellates” in 1997. In 1999, Gesa Weyhenmeyer, Thorsten Blenckner, and Kurt

Pettersson published the first paper on climatic effects on Lake Erken (Weyhenmeyer et al., 1999). Don Pierson and colleagues were performing the first remote sensing studies of Lake Erken within the Salmon project (Pierson and Strömbeck, 2000).

During the 2000s, the publication rate increased even more and more than 100 papers related to Lake Erken were published. In this decade the phosphorus forms in the sediments from accumulation bottoms were followed seasonally and also coupled to sedimentation events by Willem Goedkoop and Kurt Pettersson (2000). The studies of climatic effects continued within two larger EU projects Reflect (started in the 1990s) and Clime and with Thorsten Blenckner as leading scientist, resulting in the thesis “Climate Related Impacts on a Lake” (2001). Now modeling of lake processes also became an important tool shown in the thesis of Hampus Markensten “Climate Effects on Phytoplankton Biomass and Functional Groups” (2005). The cyanobacteria *Gloeotrichia echinulata* was subject of several studies also in this decade and Irene Karlsson-Elfgren defended her thesis “Studies on the Life Cycles of Akinete Forming Cyanobacteria” (2003). Under the leadership of Helmut Hillebrand, studies on grazing and the nutrient status of the benthic community was intensified and Antonia Liess presented her thesis “Nutrient Stoichiometry in Benthic Food Webs – Interactions Between Algae, Herbivores and Fish” (2006). Also, Lars Peters studied the benthic community with focus on the meiofauna (Peters et al., 2007). This work still continues and more information will come. During the 2000s also, fish studies reappeared with Peter Eklövs’ research group studying the adaptive morphological variation in fish populations resulting in the thesis of Philipp Hirsch: “Phenotypic Processes Triggered by Biological Invasions” (2011). The invasive species *Dreissena polymorpha* and its impacts on the lake ecosystem was investigated by Rahmat Naddafi, who defended his thesis “The Invasion of the Zebra mussel – Effects on Phytoplankton Community Structure and Ecosystem Function” in 2007 (Naddafi, 2007; Naddafi et al., 2007a, b). Finally, David Lymer made a pioneering work on bacteriophages and summarized this in his thesis “Significance and Diversity of Lake Bacteriophages,” published in 2008 (Lymer, 2008; Lymer et al., 2008a, b). A list of publications from studies in Lake Erken can be found at www.ebc.uu.se/forskning/IEG/erken/.

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Cross-references

[Eutrophication in Fresh Waters: An International Review](#)
[Light and Primary Production in Lakes](#)
[Nutrient Balance, Light, and Primary Production](#)
[Phosphor Exchange Sediment-Water](#)
[Sedimentation Processes in Lakes](#)

LOCH KATRINE

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Description

It was on April 19, 1855, that the preamble of the bill, which was to municipalize the water supply to the City of Glasgow, Scotland, was passed by a Committee of the House of Commons. It had surprisingly been a hard struggle in Committee, but the bill received the Royal Assent on July 2, 1855.

Thus, over 150 years ago, a new era was inaugurated in which the supply of water to the city was so improved that it exerted a vital influence upon a rapid expansion and development of the City of Glasgow during the second half of that century. There is little doubt that the tremendous growth of Glasgow as a great industrial city is testimony to the foresight of the civic rulers in their investment in the Loch Katrine water supply scheme.

Until 1807, the citizens had to draw their water entirely from wells, or from the River Clyde and other streams, although latterly some was sold by water cart from door to door. The quality of most of the water was questionable, and it had never been adequate, especially for the fire services.

From 1807, there had followed a period of some 45 years during which no less than three private companies – The Glasgow Company (from 1807), The Cranstonhill Company (from 1808), and the Gorbals Company (from 1848) – had attempted, not very successfully, to meet the water demand of the rapidly expanding community.

The advent of Water Companies had raised high hopes that all water problems would be solved. The Glasgow and Cranstonhill Companies, pumping the water from the River Clyde and competing with each other until they merged in 1838, were never financially successful, and that in spite of the fact that pipes were laid only where the revenue was likely to show profit. In many of the less well-off districts, no pipes at all were laid, and most of the old wells were still in use although the quality of their water was continually deteriorating. The quality of the water provided by the companies, however, was often little better, owing to inferior filtration. Moreover, the expectation that the community would be better able to fight fires were not realized, for the companies refused to keep water mains charged during the night, when the danger of fire is greatest.

An outbreak of Cholera in 1848, worst in the districts not efficiently supplied with water, had added to the growing dissatisfaction with the efforts of the companies.

Public opinion, however, had been converted gradually to the idea that the supply of water was too important a service to be left to the control of private investment. In time, the city council was converted to the same view and, on October 28, 1852, approved a resolution to take the necessary steps to bring the water supply of the city into the hands of the council, as a public trust. In December of the same year, the council secured the services of the eminent civil engineer John Frederick Bateman to advise as to the best sources of new supply. Bateman's work both at home and abroad was mainly concerned in the design and preparation of water supply schemes and also in an advisory capacity. He had already performed these tasks successfully in Manchester and Buenos Aires and in other areas.

By September 1853, Bateman had reported on seven possible schemes, one of which he recommended the Loch Katrine scheme as the only one which would meet all the requirements. How ambitious and far-sighted was this scheme may be judged from the fact that it provided for abstracting as much as 50 million gallons per day (mgd), or 220 MLD (million liters per day), whereas consumption at that time was only 14 mgd (60 MLD).

The council accepted the recommendation, however ambitious it may have seemed, and proceeded to promote the necessary bill in Parliament.

Opposition was expected from the private companies, from the landowners, and even from important sections

of cautious ratepayers (taxpayers), but the Council was hardly prepared for the argument that led to its first setback, namely that the extreme purity and softness of Loch Katrine water would constitute a real danger to health of the community because its action on lead pipes would give rise to lead poisoning. A special enquiry by scientific experts had to be made and most elaborate tests carried out before this fear was proved groundless. The admiralty then appeared in opposition, alleging that the abstraction of so much water, which would normally flow into the Firth of Forth, would seriously affect the influence of a navigable channel. This opposition proved the death-blow of the bill, which was forthwith rejected.

The Lord Provost and the Water Committee of the city council refused to accept defeat and prepared a new bill for promotion at the next session of Parliament and took all steps to remove opposition.

So successful were the measures adopted that when the new bill came before the Committee of the Commons in April 1855, the proceedings – having regard to previous experience – were somewhat of an anti-climax and there was no opposition.

Although the Act of 1855 was concerned mainly with the new source of supply from Loch Katrine, provision was also made for taking over the existing works of the private companies. Of the Glasgow Company's works, only certain sections of the city could be incorporated in the new system, and the greater part, including the pumping plant, reservoirs, etc. had to be abandoned. The Gorbals works near Barrhead, however, being modern, were retained.

The Loch Katrine scheme involved the construction of (1) masonry and earth dams across the outlets of Loch Vennachar, Loch Drunkie, and Loch Katrine, in order to secure the storage required to guarantee both the supply to the city and compensation obligations, (2) an aqueduct 28 miles (45 km) long from Loch Katrine to Milngavie, (3) Mugdock Reservoir at Milngavie, and (4) the laying of about 20 miles (32 km) of large trunk main from the reservoir to the city and about 46 miles (74 km) of new pipes for distributing the water throughout the city and suburbs. Loch Katrine is 364 ft (111 m) above the tide at Glasgow – an elevation that allows for the loss of fall in the conveyance of the water and still ensures a pressure of 70–80 ft (21–24 m) above the highest summit within the city.

The construction of these works was an undertaking of considerable magnitude, and their completion within a period of 3½ years, having regard to the difficulties encountered and the equipment then available, was a remarkable civil engineering achievement. Work commenced on May 29, 1856, upon the construction of the aqueduct, and on October 14, 1859, Her Majesty Queen Victoria, accompanied by The Prince Consort and The Princesses Alice and Helena, came through from Holyrood Palace by way of Stirling and Callander to open this great civil engineering work. She sailed up the Loch from Trossachs Pier to Stronachlachar and Royal Cottage

(so named after her visit). It had rained during the morning but cleared for the occasion. In her speech she said:

It is with much gratification that I avail myself of this opportunity of inaugurating a work which, both in its conception and its execution, reflects so much credit on its promoters, and is so calculated to improve the health and comfort of your vast population, which is rapidly increasing round the great centre of manufacturing industry in Scotland. Such a work is worthy of the enterprise and philanthropy of Glasgow and I trust it will be blessed with complete success. I desire that you will convey to the great community which you represent my warmest wishes for their continued prosperity and happiness.

After a prayer of dedication and thanksgiving, Her Majesty turned the handle placed for the purpose, and, amid the booming of cannon repeated at the Trossachs and Callander, the Loch Katrine Water Works were declared duly inaugurated. The news was telegraphed to Glasgow, Edinburgh, and Stirling. Edinburgh and Stirling castles at once sent forth their salvos of artillery, and in Glasgow, the city bells rang merrily in celebration of the event. At Her Majesty's request, the royal party was conducted at the sluice, so that they might themselves see the water flowing for the first time from Loch Katrine toward Glasgow – there to begin the beneficial work of safeguarding the health of the community and stimulating the development of the city and its industries.

At a Banquet given in his honor to commemorate the completion of the Loch Katrine Water Works, Bateman said in his speech:

I leave you a work which I believe will with very slight attention, remain perfect for ages, which, for the greater part of it, is as indestructible as the hills through which it has been carried: a truly Roman work. Not executed, like the colossal monuments of the East, by forced labour at the command of an arbitrary Sovereign, but by the free will and contributions of a highly civilised and enlightened City. It is a work indeed which surpasses the greatest of the nine famous Aqueducts which fed the City of Rome; and amongst the works of ornament and usefulness for which your City is now distinguished and will hereafter become famous, none, I venture to say will be counted more credible to your wisdom, more worthy of your liberality, or more beneficial in its results, than the Loch Katrine Water Works.

The population of the city enjoyed their bountiful supply of wholesome water, but the story is told of an old lady who lived in Monteith Row and who, all her life, had been in the habit of carrying all the water she required from the Arns Well in Glasgow Green, a practice she insisted in continuing even after the Loch Katrine supply was available. When the authorities decided to close Arns Well, which had become polluted and a menace to public health, she was very indignant and complained bitterly to a neighbor who tried to soothe her by saying "Hoots woman why need you fash yourself you've got gravitation water in the house," to which the old dame retorted "Huh, I just canna thole that new water, it's got neither taste nor smell."

The event was of national interest and "Punch" even produced an article:

Glesca's just a' richt the noo,
She has Loch Katrine brought her,
Ever she had mountain dew,
Noo she rins wi' mountain water.
Hech the blessin'! ho the boon!
Tae ilka drouthie Glesca body,
Sin' there's water in the toon
Owre eneuch to mak its toddie.
Glesca chiels, a truth ye'll learn
New to mony a Scot, I'm thinkin'
Water siblins ye'll discern
Was na gi'en alone for drinkin'
Hauns and face ye'll scrub at least,
Frae ane until anither Monday,
Gif nae Sabbatarian bust
Stop your Waterworks on Sunday

In only 12 years later, consumption had almost reached the design figure of 14 mgd (60 MLD) that according to estimates should not have been reached until 1,900. There was no doubt that the new abundant water supply was an important factor in the development and growth of the city. It was also found that the aqueduct could carry only about 40 mgd (180 MLD) instead of the estimated 50 mgd (225 MLD). A substantial extension of the works became urgent. The necessary parliamentary powers were secured by the Acts of 1882 and 1885 to:

1. Construct a second service reservoir at Craigmaddie
2. Construct a second line of aqueduct from Loch Katrine to the reservoir in Milngavie
3. Increase the storage capacity of Loch Katrine by a further raising of the level by 5 ft (1.5 m)
4. Impound the waters of Loch Arklet and convey them into Loch Katrine through a connecting aqueduct
5. Increase the maximum quantity that might be drawn from Loch Katrine to the city in any 1 day from 50 mgd (225 MLD) to 110 mgd (500 MLD)
6. Lay two additional trunk mains from Milngavie Reservoirs to the city

By the completion of these works in installments by the year 1914, the storage capacity of Loch Katrine and Loch Arklet and the aqueduct delivery capacity were more than doubled, and ample provision seemed to have been made for many more years.

By the year 1911, the population supplied had increased to over one million and the average daily consumption to nearly 68 mgd (310 MLD). Over the previous 30 years, this represented an increase in population of 50% and in consumption of about 75%. It was therefore clear that the existing storage would not be adequate for any further great increase in demand, and a new problem thus presented itself. Two solutions were found and approved by the Glasgow Corporation, one a more permanent solution and the other an interim one. For various reasons the interim was proceeded with first.

The interim solution involved a further and third raising of the level of Loch Katrine and the inlet at Royal Cottage

by 5 ft (1.5 m). With these works completed and with the loch at its new top water level, the undertaking could draw upon a depth of 17 ft (5 m) instead of the original 7 ft (2 m), providing a storage capacity sufficient to supply the city with water for a period of 7 months without rainfall on a consumption basis of 70 mgd (320 MLD) or 5½ months at the then present consumption of approximately 90 mgd (410 MLD). Although storage in Loch Katrine and Loch Arklet would be three times the original capacity under the 1855 Act, the yield of the drainage area had not been in any way increased.

For the more permanent solution, a new source of supply which would increase the available yield of water was essential, and in 1914, a bill was promoted to impound the water of Loch Voil and Loch Doine and convey to Loch Katrine by tunnel. The unfortunate rejection of this scheme by the Parliament is a matter of history. It was a bold, ambitious, and far-sighted scheme, which, had it materialized, would have provided an additional 58 mgd (264 MLD) and would have solved all problems of water resources for many years.

An alternative source was ultimately found in Glen Finglas, and, by the Act of 1915, powers were secured to impound the Rivers Turk and Finglas by the construction of a dam, thus creating a reservoir with a capacity greater than that of Loch Arklet, although considerably less than that of Loch Voil. Unfortunately because of the First World War, the work could not be started, and by 1918, prevailing high costs dictated the adoption of the above interim solution and this was finally completed in 1926.

The long period of industrial depression between the two World Wars caused the Glen Finglas scheme to be kept in reserve as a prudent provision for future needs.

It was 30 years before demand again reached the peak demand, and in the intervening depression years, it dropped to 11 mgd (50 MLD) below the peak. Then partly due to improved distribution, attributable to extensive new works of the post war period including the Clyde Water Tunnel, the demand curve began to rise steeply, the Chief Water Engineer and General Manager recommended an early start to the Glen Finglas Scheme, albeit a modified scheme.

The modified scheme provided surplus water from the Glen Finglas intake weir across the River Turk and a tunnel to Loch Katrine and later the construction of the dam at Glen Finglas.

The first part was completed and inaugurated on October 23, 1958, by HRH The Princess Margaret.

The second part, that of the dam, was completed in 1965. The dam is 115 ft (35 m) and 800 ft (243 m) at crest level, creating a storage of 3,500 million gallons (15,900 million liters) supplying an average of 20 mgd (91 MLD) to Loch Katrine through a horseshoe tunnel 8 ft (2.5 m) in diameter laid to a gradient of 1 in 3,000 about 2½ miles (4 km) long. The tunnel driving was limited to two headings, one from each end, and the junction of the discrepancy of the two headings was less than ¼ inch (6 mm) in line and level. Control of the tunnel drive was exercised by means of roof stations set in by theodolite and level. These were used by the tunnel gangers to mark out the position of the shot holes for each round of explosive. It was necessary to make a comprehensive triangulation survey across the hills with measured base lines in Glen Finglas and at Loch Katrine to ensure that the two tunnel headings would meet successfully. The rock encountered in the tunnel was mainly metamorphic grit and schist, and the tunnel was dry on the whole.



Loch Katrine, Figure 1 View of Loch Katrine from Ben A'an (Scottish Water).

As the population of the city reduced in the subsequent years, from the original high in the 1930s of 1,250,000 to eventually 700,000 in the 1980s, there was little need to consider new or additional sources, this in spite of the closure of the Gorbals works near Barrhead.

However, there was a need to consider the water quality of the Loch Katrine supply which had, from its inception, required no treatment, the quality being such that only disinfection by chlorination was necessary and that only apparently necessary since the 1930s.

In addition, reorganization of the water industry in Scotland in the 1990s saw the whole of the water industry in Scotland coming under Scottish Water. Investment was required to modernize the industry and for the need to upgrade the treatment of water, in particular, for microorganisms or bacteria and cryptosporidium, to meet the UK and European Standards (European Directives and WHO Standards). Indeed, the city suffered a cryptosporidium contamination in 2002 when 160,000 people were told to boil their water after bacteria got into the supply. The treatment works at Milngavie is scheduled to be completed in 2007 including the construction of a 240 MLD (50 mgd) direct filtration plant, modification to the existing Balmore Water Treatment Works pumping station to allow the conjunctive use of 150 MLD (30 mgd) into the Glasgow supply area, and other ancillary work.

The Balmore Water Treatment Works was completed in 1997 for treating water from the new Loch Lomond source to serve other areas of Scotland. The Loch Lomond Aqueduct conveys a pumped raw water supply of 286 MLD (60 mgd) to the treatment works. The two aqueducts cross each other north of Milngavie (the 400 MLD (88 mgd) supply from Loch Katrine and the 286 MLD (60 mgd) from Loch Lomond). In order to allow the conjunctive use of 150 MLD (30 mgd) from Loch Lomond into the Glasgow supply, a cross connection was made. Thus, the final link will be in place to continue the 150 years of investment in Loch Katrine water (Figure 1).

Cross-references

[Bathymetrical Survey of the Scottish Freshwater Lochs, 1897–1909](#)
[Kingairloch Hydroelectric Scheme](#)

LOUGH

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Lough

Lough is an anglicized form of loch which is Irish Gaelic (pronounced Gailik). Loch is entirely used in Scotland with one exception – the Lake of Menteith near Aberfoyle. Lough is used in Ireland almost exclusively. It was

introduced by British administrators as the anglicized form of loch, but lough is also used for some water bodies in the north of England.

Lough Neagh in Northern Ireland is the largest lake in Ireland and the largest in area in the United Kingdom. The three lakes on the Shannon are Lough Allen, Lough Ree, and Lough Derg.

LOUGH NEAGH

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Location

Lough Neagh is located in Northern Ireland with its geometric center at latitude 54° 36'N and longitude 6° 23'W. Its Irish grid map reference is J 3032 3750. Politically, it is totally within the United Kingdom, although some of its contributory rivers have sources in the Republic of Ireland.

Physical parameters

Six major rivers flow into Lough Neagh: the Main, Six Mile Water, Upper Bann, Blackwater, Ballinderry, and Moyola. There is one outflow: the Lower River Bann which flows into the sea. The Lough Neagh and Lower River Bann Basins include 43% of the surface area of Northern Ireland and about 30% of the Northern Ireland population. The two Basins are predominantly agricultural in character, but there are areas of significant population in Craigavon, Antrim, Ballymena, and the Coleraine–Portrush–Portstewart triangle. There are no nationally important industries, but there are numerous locally based industries which, collectively, contribute measurably to the overall United Kingdom economy. The water surface area of Lough Neagh is 385 sq. km, making it the largest lake in extent in the British Isles. The inflowing catchment area is 4,465 sq. km and the outflowing basinal area is 925 sq. km: a combined area of lake and basins of 5,775 sq. km. The Lough has a maximum depth of about 30 m, an average depth of 9.5 m and a total capacity of about 3,636 million cubic meters.

The geological structure of the area is of a folding and faulting nature, formed in Tertiary times to some 450 m of chalk layers, immediately after the outpourings of the East Antrim basalts. Most of the area is overlain by glacial deposits (mainly boulder clay) with more recent deposits of mainly river gravel (Figure 1).

Flow regime

The flow regime is controlled artificially by vertical sluice gates, of which there are three separate installations. At the outlet from the Lough, gates, built on a rock outcrop, control the Lough level to a statutory requirement of between 15.24 and 15.39 m above the mean sea level, provided that climatic excesses do not make that preciseness of control impossible. The effective control of the Lough outflow

control and monitor because they are either concentrated discharges from animal or poultry units, or runoff and seepage from land which has been either organically or inorganically treated. Toxic waste can pose a threat, but waste disposal measures generally preclude toxic discharges to watercourses.

Eutrophication always has been looming in Lough Neagh because of its slow volumetric turnover time of about 12 months and its predominantly shallow depth below a relatively large surface area. The major eutrophication-inducing factor has been the phosphorous loadings emanating from sewage treatment works and agricultural sources, but this aspect has been reduced significantly by heavy expenditure on tertiary treatment of sewage and on isolating agricultural discharges wherever this has been practical. The Lough cannot be classified as eutrophic, but continuous monitoring is undertaken to guard against adverse trends toward eutrophication.

Sedimentation

This is not a particularly prominent facet of Lough Neagh or any of its basins. Normal erosion does take place in the rivers, of course, but it is not of such a magnitude that watercourses change their profiles or that very much remedial work is needed to protect banks and adjacent property. Dredging requirements are minimal. The regolith material from the inflowing rivers settles mostly, eventually, in the Lough, and in the deepest parts there are sand and gravel deposits that are commercially very valuable and providing a major proportion of the sands and gravels used industrially in Northern Ireland.

Usage

Basically, Lough Neagh and its basins are underused but the following uses do prevail.

Fisheries: The important fish are the salmon and the eel, both migratory and supporting viable commercial ventures. Salmon enter the river system from the sea in May, June, July, and August and are subject to netting at the tidal estuary of the Lower River Bann and to trapping at the two sluice structures in the river. Further upstream and in the Lough, some angling and fishing from boats take place. Eels, after spawning in the western Atlantic Ocean, move into the Lower River Bann when 3 years old from March to May, and travel back to the spawning grounds when 8 years old or more. On both journeys, they are caught commercially for major marketing ventures in Great Britain and in the Netherlands.

Water supplies: Approximately two-thirds of the public water supplied to the Belfast conurbation and its contiguous areas are drawn from Lough Neagh. In addition, public water is taken into the northeastern areas of Northern Ireland and into the Craigavon area. Treatment is at source, at a level or purity which more than satisfies the standards set by the EU. The amounts taken are substantial, but nevertheless, are very small in relation to the total volume of water in the Lough. Future increases in water

supplies to the general Belfast area would be provided for by additional abstractions from the Lough.

Drainage: The Lough and its basins are natural gravitational drainage areas so that flooding virtually is nonexistent. The statutory controls of the Lough surface levels emanate from successive lowerings of the Lough by some 2 m which released an additional 20,000 ha of peripheral land for agricultural usage.

Navigation: The Lower River Bann is navigable by small craft for its whole length as navigation ways are provided at all three sluice structures. The Lough itself is used for sailing, but the amount of sailing undertaken falls far short of the enormous potential for the activity which the Lough could provide.

Tourism and Recreation: As with the sailing, the potential is not realized anywhere near to the full extent. Market forces do not attract extensive tourism to Northern Ireland and the relatively low population density of Northern Ireland means that the number of people seeking recreational facilities in the Lough Neagh area is not very large.

Nature Conservation: There are several areas of scientific interest around the Lough and some areas of natural beauty; all overseen admirably by relevant Government agencies.

Management

Surprisingly, there is no overall management authority for Lough Neagh and the two basins. Management of the various interests is vested mostly in relevant Government Departments and Agencies, who accept their responsibilities generally with both diligence and enthusiasm. However, these authorities operate from a variety of resource bases, which make it difficult to get a consensus for the acceptance of the proportioning of contributions toward the cost of creating and operating a Lough Neagh Conservancy or similar body. Considerable progress toward the creation of a single management body has been made but that ultimate goal has yet to be achieved.

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M

MACEDONIAN LAKES

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Skopje, Macedonia

Introduction

The Republic of Macedonia is a land-locked country located in the central part of the Balkan Peninsula, covering an area of 25,713 km², with about two million inhabitants and with annual water resources per capita of about 3,150 m³.

From the hydrographic aspect, the territory of Macedonia is a unique natural basin in the Balkan Peninsula and wider because more than 80% of the water resources are formed on the territory of the country in four river basins: Vardar, Crn Drim, Strumica, and Juzna (South) Morava river basin. The river basin areas of Vardar and Strumica River gravitate toward the Aegean Sea, covering 87% of the total territory. The river basin area of Crn Drim River gravitates toward the Adriatic Sea (13% of the total area), and the river basin area of Juzna Morava whose territory is insignificant gravitates toward the Black Sea.

There are three major natural lakes in Macedonia: Ohrid, Prespa, and Dojran Lake. The locations of these lakes are shown in the map in [Figure 1](#). All of them are shared with the neighboring countries. The lakes belong to the group of the oldest European tectonic lakes.

Ohrid lake

General

Lake Ohrid is the biggest lake in the Republic of Macedonia and is located in the southwest part of the country, on the border between Macedonia and Albania. It is situated on 695 m.a.s.l., and it covers an area of 358.2 km², out of which 230 km² belongs to Macedonia

and the rest to Albania. The total watershed area covers 2,340 km², out of which 843 km² belongs to Macedonia. The shoreline is 87.5 km long, out of which 56 km belongs to Macedonia, the maximum length is 30.8 km, and its maximum width is 14.8 km. The average depth is 164 m and maximum depth is 289 m.

The Lake is surrounded by the mountains Mokra (Mokra Planina – 1,589 m.a.s.l.) and Jablanica (1,945 m.a.s.l.) on the Albanian side, as it is shown in [Figure 2](#), and by the karstic mountain Galicica (2,255 m.a.s.l.) on the eastern side.

History

Lake Ohrid is Europe's oldest lake (between 4 and 10 Ma ago) and is among the oldest in the world. By its origin, the Lake is a tectonic lake and belongs to the so-called group of "Desaretian lakes," named by an ancient region Desaretia. The Lake was formed in the tertiary period prior to the glaciation.

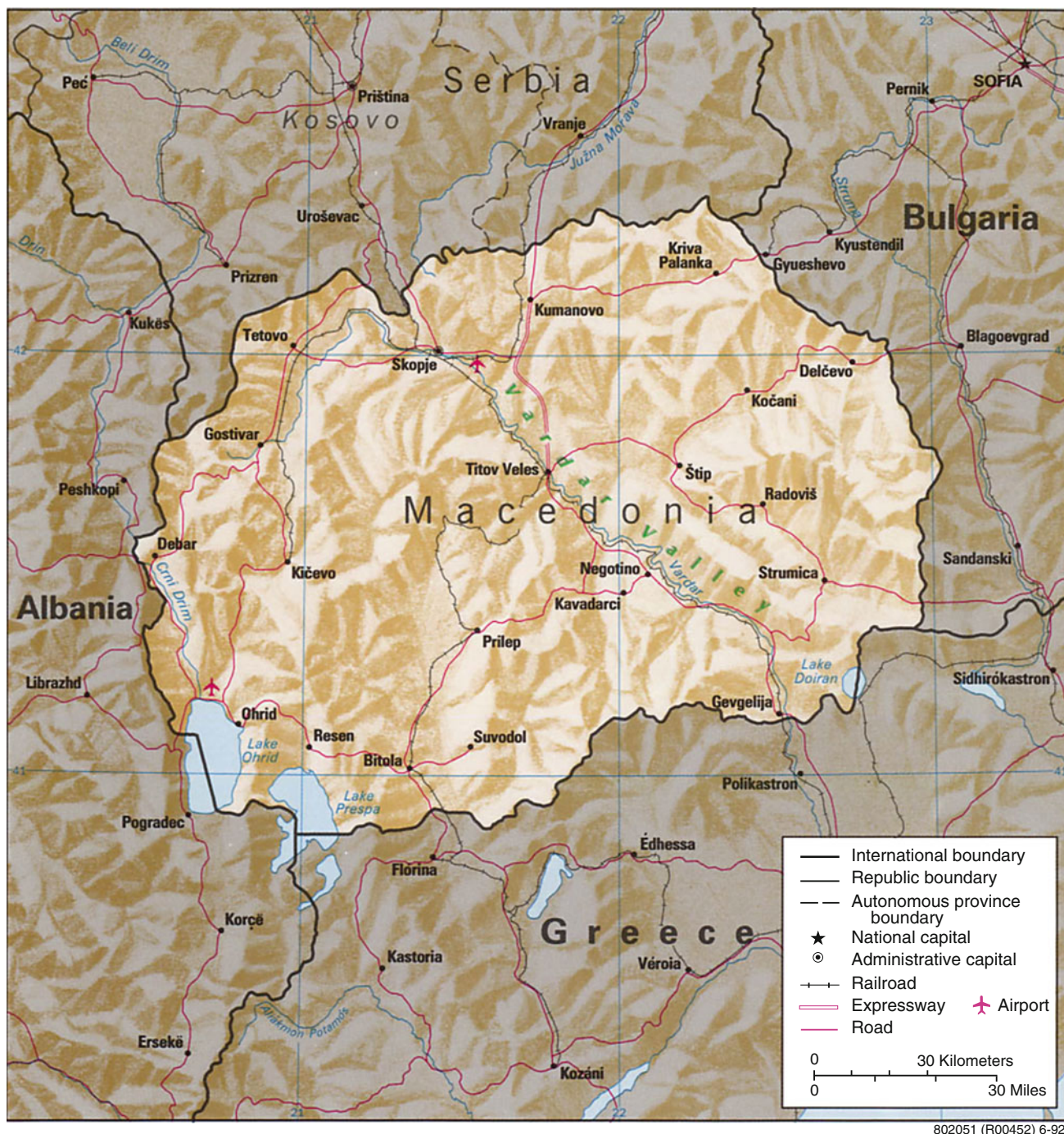
Due to rich history and unique flora and fauna, Lake Ohrid was declared a UNESCO World Cultural and Natural Heritage Site in 1980.

Geology

The wider zone in this part of the country consists of a complex of Paleozoic metamorphic and magmatic rocks which makes up the foundation bedrock. The Mesozoic rocks from the Triassic Era show types of faces, such as (1) sediments consisting of conglomerates, sands, and clays and (2) carbonate sediments, such as slate, bank and massif limestone, and dolomites. These sedimentary formations are intensely rugged, broken, and karstified. Tectonic forces formed much of the terrain in the Lake Ohrid watershed. It has been shaped by both Hercynian and Alpine orogenesis.

Hydrographic features

Lake Ohrid is the seventh deepest lake in Europe, with a volume of 50.7 billion cubic meters. Most of the water



Macedonian Lakes, Figure 1 Map of Macedonia.

comes from numerous surface and underground springs. The surface springs mostly lie along the southern shore on the Macedonian side at location St. Naum (average $7.5 \text{ m}^3/\text{s}$) and close to city of Podgradec in Albania (average $2.5 \text{ m}^3/\text{s}$). There are about 40 rivers and springs which flow into the Lake (23 on the Albanian and 17 on

the Macedonian side). During summer, most of them dry out, whereas the rivers Sateska (average $6.2 \text{ m}^3/\text{s}$), Koselska (average $1.3 \text{ m}^3/\text{s}$), and Corava (average $1.5 \text{ m}^3/\text{s}$) have significant inflow that charges the Lake. On the Albanian side, the river Podgradeci has an average discharge of $0.3 \text{ m}^3/\text{s}$.



Macedonian Lakes, Figure 2 Ohrid Lake.

In the beginning of the previous century, J. Cvijic stated the assumption that the water of the adjacent Lake Prespa, which has 158-m-higher water level, flows through the karstic areas of the mountains Galicica and Suva Gora. The two lakes formed one lake at their earliest stage of existence. By using natural isotopes, it has been proved that these two lakes are connected hydrographically. Evidence has confirmed that more than 50% of the water from the springs near St. Naum comes from Lake Prespa. The discharge of the karst water coming out of Galicica Mountain is $5.2 \text{ m}^3/\text{s}$.

The Lake has one outlet, the River Crn Drim, which flows to the Adriatic Sea. This outlet is man controlled, and according to the needs of the downstream power plants, it provides about $22 \text{ m}^3/\text{s}$ or a total annual outflow of 694 million cubic meters. Downstream, there are two dams on the Macedonian territory and three on the Albanian side, with a main purpose – energy production.

Climate

The climate of Lake Ohrid is classified as a local-continental type. Mean annual air temperature is 11.4°C . The average annual rainfall in the Lake basin is about 759 mm. The water temperature in the deepest layers of Ohrid Lake is approximately 6°C , while the surface layers may have up to 24°C , and even up to 26°C closer to the shore. The Lake never freezes over.

Flora and fauna

Due to the low level of nutrients, the lake is classified as oligotrophic lake. This Lake is distinctive shelter of large number of freshwater organisms originating from the tertiary period, whose close relatives can be found in fossil forms only. Due to the geographic isolation and permanent living

conditions, the existing tertiary living forms further evolve into new taxonomic classes, including subspecies, species, and even entire families of newly evolved organisms. For this reason, the lake is also called “museum of living fossils.”

Most of the endemic species are benthic forms (e.g., *Pyrgula macedonica* (freshwater snail; Stankovic, 1960), *Ochridaspongia rotunda* (freshwater sponge; Gilbert and Hadzisce, 1984)), but there are also a number of endemic plankton species (e.g., *Cyclops ohridanus* (zooplankton) and *Cyclotella fottii* (phytoplankton) both described by Stankovic (1960), as well as fish (e.g., *Salmo letnica* [Ohrid trout; Sell and Spirkovski, 2004])).

The fish population of the Lake comprises 17 native species belonging to four families: *Salmonidae* (2 species), *Cyprinidae* (12 species), *Cobitidae* (2 species), and *Anguillidae* (1 species). One of the most fascinating species in the lake is the European eel, which comes to Lake Ohrid from the distant Saragossa Sea. Due to constructed dams on the river Crn Drim which stopped the migration of eels, the reproduction is enabled with providing young eels directly into the lake from other sources.

The lakeshore reed beds and wetlands provide critical habitat for hundreds of thousands of wintering water birds, including rare and threatened species, such as the Dalmatian Pelican, Ferruginous Duck, swan, Spotted Eagle, and Eastern Imperial Eagle.

The Lake's flora is dominated by various types of algae and superior water plants. Typical for this lake is the underground plant called “hara” that forms a continual ring in the lake's bottom at the depth of 6–15 m.

Cities

There are three cities on the Lake's shores: Ohrid and Struga on the Macedonian side and Podgradec on the

Albanian side, with total number of about 200,000 inhabitants (in 2003). The main economic activities in the region are tourism and agriculture.

Prespa lake

General

There are two lakes in the Prespa valley: Big Prespa Lake and Small Prespa Lake. Big Prespa Lake is shared among the Republic of Macedonia, Albania, and Greece. It has a surface area of 274 km², out of which the bigger part (65%) belongs to Macedonia, the southeast part (about 17%) belongs to Greece and southwest part (about 18%) belongs to Albania. Maximal length of Lake Prespa is about 28 km, maximal width is about 17 m, and the average width is about 10 km. Maximal depth of Lake Prespa, according Cvejic in 1911, is 54 m, but during this period, it has been less than 50 m deep, while the average depth is between 15 and 17 m. Small Lake Prespa belongs fully to Greece. The location of the lake is shown on the map in Figure 1, while Figure 3 presents the satellite image of both lakes.

They are the highest tectonic lakes on the Balkans, standing at an altitude of 853 m.a.s.l. There are two islands in Big Prespa Lake: “Golem Grad” (also called St. Peter) and “Mal Grad” (also called St. Paul). The island “Golem Grad” is declared for a reservation, for its specific geomorphology, its flora and fauna, and its historical past.

History

Lake Prespa, together with Lake Ohrid, is between the oldest lakes (2–3 Ma) in Europe that, according to Cvijic's (1911) estimation, originated from Pliocene period. These



Macedonian Lakes, Figure 3 Satellite image of Prespa Lakes.

two lakes are not linked on the surface, but the water from Lake Prespa through the karstic area of the mountain Galicica flows into Ohrid Lake (Anovski et al., 1980).

Geology

Lake Prespa has tectonic origin and fulfills the deepest part of Prespa valley. It is located at the touch of three different geological masses, the granite massif on the east side Pelister, karstic massif of Galicica on the west, and Suva Gora (Dry Mountain) on the south side. The Ohrid–Prespa region is characterized by very complex geological-tectonic structure where rocks, from the oldest Paleozoic formations to the youngest Neogene and Quaternary, have been represented. The terrains which make this region belong tectonically to the west Macedonian tectonic zones within the Dinarides (Helinides) formed in the period of Hercynian and the Alpine orogenesis.

From hydrogeological aspect, all types of aquifers have been presented (confined, scattered, and karst type), but the most significant is the karst type of aquifers, of which the mountain Galicica has been formed as horst-anticlinorium between Prespa and Ohrid Lake, with numerous represented karst forms, such as karst fields, sinks, and sinkholes, as well as the underground channels significant for the genesis of Ohrid and Prespa Lake.

Hydrographic features

Watershed of Lake Prespa is about 1,200 km². Main tributaries that feed the lake are the rivers Istocka, Golema, Pretorska, and Brajcino River on the Macedonian side and river Stara in the Greek part of the watershed. Total volume of Lake Prespa is 4.8 billion cubic meters. Through the karstic area of the mountain Galicica, the water from this Lake flows into Lake Ohrid. There is no surface outflow from Lake Prespa.

Natural oscillations of the level of Lake Prespa are characteristic and, according to Cavkalovski (1977), appear every 20–25 years. For the period 1961–1986, there were average oscillations of the water level, but from 1986, the water level started drastically to drop-down; the absolute annual minimum of the water level of –445 cm occurred in 2002. This extreme reduction of the water level is resulting due to the anthropogenic impact (use of the water from the lake for irrigation purposes) as well as due to the climate change. The records of the water level for the last few years show increase of the water level and stabilization of the water balance of the lake.

Climate

In the Lake Prespa watershed, the following types of climate appear: warm and cold sub-Mediterranean climate; submountainous and mountainous sub-Mediterranean climate; and, on the highest elevations, respectively, subalpine and alpine climatic types. The average annual air temperature is about 9.5°C for the city of Resen, while the average annual water temperature of the lake is 13°C, with a maximum temperature of 22°C in August and a minimum of 4°C in February. Average annual sum

of precipitation around Lake Prespa is about 600 mm. During extremely cold winters, upper littoral zone of Lake Prespa freezes, although for a short time.

Flora and fauna

There is high habitat diversity in the Prespa basin, with a flora of more than 1,500 species. The indigenous fish species are all endemic, while endangered mammals include brown bear *Ursos arctos*, wolf *Canis lupus*, chamois *Rupicapra rupicapra balcanica*, and European otter *Lutra lutra*. The area is especially important for water-birds, notably the largest breeding colony of Dalmatian Pelicans *Pelecanus crispus* (listed by IUCN and BirdLife International as Vulnerable) in the world as well as a substantial number of White Pelicans *P. onocrotalus* and Pygmy Cormorants *Phalacrocorax pygmaeus*. Since 1994, the strict natural ornithological reserve EZERANI has been promoted with its inclusion on the world Ramsar list. Regarding fish, Lake Prespa is not very rich with fish. Among the six endemic species of fish, the Prespa bleak (*Alburnus belvica*) and the carp (*Cyprinus carpio*) are the most important.

Population

In the Prespa Lake watershed, there are 5,000 inhabitants in 12 villages on the Albanian side, 1,600 inhabitants in 13 villages on the Greek side, and about 17,500 inhabitants on Macedonian side, situated in 40 settlements. The biggest settlement in Macedonia is the city of Resen as administrative center of the municipality. The main activities of the population are agriculture (dominated by fruit production in Macedonia), tourism, fishing, and food processing industry.

Dojran lake

General

Lake Dojran is the smallest tectonic lake in Macedonia, situated in the southwest part of the country, occupying an area of 43 km². The western, larger part (27 km²) belongs to Macedonia, while the eastern, smaller part (16 km²) belongs to Greece. The water level of the lake is at 148 m.a.s.l. The lake is rather shallow, and the deepest part is about 10 m. The shallow character of the lake is visualized in Figure 4. On the north, the basin of the lake is enclosed by the mountains Belasica and Boska; on the west, with the mountains Dub and Kara Balija; east, Krusa; and on the south, is opened to the valley of the river Gjolaja and toward the Thessalonika Plain.

History

The Lake Dojran basin was created during the young Pliocene, while the lake was created in Pleistocene. Actually, Dojran Lake is relict reminder of former Pleistocene Peon Lake, which was occupying an area of about 127 km².

Geology

Dojran Lake and wider area are located on the boundary areas of two large geotectonic units, actually on the border between the Serbian-Macedonian massif on the east and Vardarian zone on the west. Terrain of this region is made of Precambrian, Paleozoic, Mesozoic upper Eocene, and Neogene's Quaternary.

Hydrographic features

The Lake is filled with water through underground springs and from Golema Reka, Toplec, and other rivers. The



Macedonian Lakes, Figure 4 Dojran Lake.

Lake flows out through the river Gjolaja on the Greek territory if certain level of the water is achieved. The total watershed covers the area of 272 km², out of which 92 km² belongs to Macedonia, while 180 km² to Greece.

The level of Lake Dojran has dropped considerably during the period from 1988 to 2000. Individual lake zones and groups of species were endangered. Birds were threatened first due to drying up of the reed belt which was the most important nesting place for birds. The main reasons for this level decrease were the extraordinary dry years and overexploitation of the water for irrigation from both the Macedonian side and the Greek side.

In the period from 1988 to 1995, the depth of the lake was reduced to 4 m. In the same period, the annual sums of the rainfalls were only 80% of the average multiannual sums of rainfalls. This was reflected also in the lost of water volume of the lake from 229.3 million cubic meters in 1988 to 85 million cubic meters in 1995, which means that only 38% of the original volume of the lake was still existing. The surface area of the lake was reduced to 79% of the starting surface area (Skoklevski, 2003).

In order to save Lake Dojran, the Macedonian authorities in 2002 put under operation a system for recharging of the lake with groundwater. The groundwater is abstracted from 10 wells in the area of Gjavato Pole, with total capacity of 1,000 l/s, and transported by 20 km of pipeline toward Lake Dojran. The results are already positive, and together with improved hydrological conditions, the water level started to rise.

Climate

The watershed of Lake Dojran has sub-Mediterranean climate with higher monthly average air temperatures and lower sums of annual rainfalls. The average annual air temperature is between 13°C and 15°C, while the average annual sum of rainfalls is 620 mm.

Lake Dojran is the warmest natural lake in Macedonia. The water temperature of the lake goes up to 27°C in August and up to 6°C in winter period.

Flora and fauna

Lake Dojran is a eutrophic lake rich with phyto- and zooplankton. The blue-green algae (Cyanophyta) are the most abundant in the phytoplankton. During August and September, their biomass is so large that the whole lake surface is covered by water bloom. Zooplankton is represented by 23 crustacean and several shell species. Due to the high plankton production, Lake Dojran is rich with fish species (about 15 species; 4 of them, endemic). The presence of freshwater crab (*Potamon ibericum*) is very significant.

In the period of the drastic drop-down of the lake, accelerated eutrophication has led to intensive sedimentation and a dramatic reduction in the epibenthic communities, as well as serious changes in the structure of the algal microflora. Although currently severely disturbed, the benthic community likely still has enough genetic potential to completely restore itself.

Cities

There are only two settlements on the Macedonian side, Star and Nov Dojran, with total population of about 3,700 inhabitants. On the Greek side of the lake, there is one settlement, Dojrany, with similar number of population. The main activities of the inhabitants are tourism and fishing. Fishing on the lake is done in a primeval way with the help of birds and is a unique way of fishing in the world. The birds, by their presence, make the fish to enter into the special bounds of cane called "mandri" from which the fish cannot escape.

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Cross-references

Dams and Reservoirs in Macedonia

MARACAIBO LAKE

Rhodes W. Fairbridge (Deceased)

Definition

Lake Maracaibo is a large lake of mixed brackish marine and freshwater origin, located in the NW part of Venezuela covering about 13,510 km². It is about 213 km long and up to 115 km across. It was discovered in 1499 by Alonso de Ojeda, who named the country "Little Venice" because of the thatched huts on stilts around the lake shore. It is one of the world's great petroleum producers, where oil was discovered in 1917. Today the horizon is studded with offshore oil derricks.

The lake is shallow, an area of tectonic subsidence. Its depth is 35 m in places, and it is connected to the ocean via Tablazo Bay and the Gulf of Venezuela to the Caribbean.

Ocean-going tankers cannot negotiate the shallow strait and need to be loaded at the city of Maracaibo. The lake is fed by the Catatumbo River, which rises in the Cordillera Oriental of Colombia.

MARIB DAM AND IRRIGATION PROJECT

Rajib Chakraborty

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The glorious past

The Republic of Yemen is situated in the southern fringe of the Arabian Peninsula. It is considered a most attractive country to the tourists from around the world for its excellent scenic beauty and archeological heritage. The Marib region is located at the eastern part of the country and was an ancient historical glory of Arabian Peninsula with a highly developed agricultural economy (Figure 1). The Marib capital of Shebans, the religious and political center of the kingdom, was the place where both intellectual and material evolution originated as well as culminated. It was here that the most perfect specimen of an ancient irrigation system was constructed, being a complex and technically highly elaborate project. The Marib dam, across Wadi Abida at the mouth of the Jabal Balaq gorge, was one of the world's oldest manmade dams constructed about the sixth century B.C. (Figure 2).

The dam was a diversion structure having a small storage capacity and was the largest of a series of smaller dams built during later centuries. The smaller dams were built by the local people to divert water to their fields. The old Marib dam was about 14 m in height. The dam was silted up in the course of time with sand and sediment load brought in by the wadi (wide-bedded river) waters. The old dam was affected by heavy floods and also had

undergone recurring processes of reconstruction. The catastrophe, which occurred toward the end of the sixth century A.D., damaged the dam irreparably. This incident is described in the Holy Quran as the "Mighty Deluge." The remnants of the old Marib dam and Sheban civilization can be seen in the vicinity of the project area. The Marib region, therefore, is invested with archeological heritage and attracts tourists and archeologists from around the world.

Development of the project

The structure of Marib's society is based on a tribal system. Five to six main tribes live here and dominate the area. In tribal law, the head of the tribe (Sheikh) is the most powerful man and the decision maker. The old way of spate irrigation was to utilize the flood by diverting it to agricultural land by constructing bund across the widespread river (wadi). According to tribal irrigation law, the upstream farmers retain the water for a certain time period; then, they are obliged to release to their neighbors downstream and so on until the water is completely infiltrated. Erratic rainfall in the area and gradual extension of agricultural land obviated the need of pump irrigation especially in the downstream area. Though people are trying their best to cultivate the land by pumping and conventional spate irrigation depending on the nature, a major portion of the fertile wadi bed comes under the sand dunes, and the groundwater table gradually reduces. To restore the prosperous agricultural past of the Marib area, with a financial grant from the Government of Yemen and Abu Dhabi Fund for Development, the Marib Dam and Irrigation Project was conceived in 1976 by replacing the old spate irrigation system through a modern and economic perennial irrigation system.

After a preliminary investigation and the submission of a Feasibility Study in June 1978, the concept of spate irrigation was changed in favor of total agricultural development of the area based on assured irrigation water from Wadi Abida by providing a storage dam and main line canal irrigation system as Phase I of the project. The project is under direct control of Eastern Region Agricultural Development Authority (ERADA), a wing of Ministry of Agriculture and Irrigation. Detailed designs and tender documents for the dam project were formulated in 1981.

After a tendering process followed by construction, the new Marib dam was completed in 1986. The work for main lined canal system was also completed in 1986. Concurrent with the formulation of the Marib dam project, there have been significant economic developments in the area. Moreover, the discovery of oil reserve about 60 km north-west of the project area has added to economic upsurge. In 1987, the Government decided to extend the scope of work by implementing the secondary canal network in Phase II. In September 1989, the first water conveyance test was conducted. The details of the scheme showing the location of the main dam, diversion structures A and B, and main canals A, B, BN, BB, and BS are presented in Figure 3.



Marib Dam and irrigation project, Figure 1 Location of Marib in the Republic of Yemen.



Marib Dam and irrigation project, Figure 2 Remains of the original Marib dam in the sixth century B.C.

Due to the civil unrest in the area among different tribes, the contractor was unable to complete the work. In the month of March 1990, after completion of only 6% of Phase II, the contractor started demobilization, leading to termination of the contract. Installation of precast units and

construction of different structures for secondary canalette were left incomplete, and the system was un-operational.

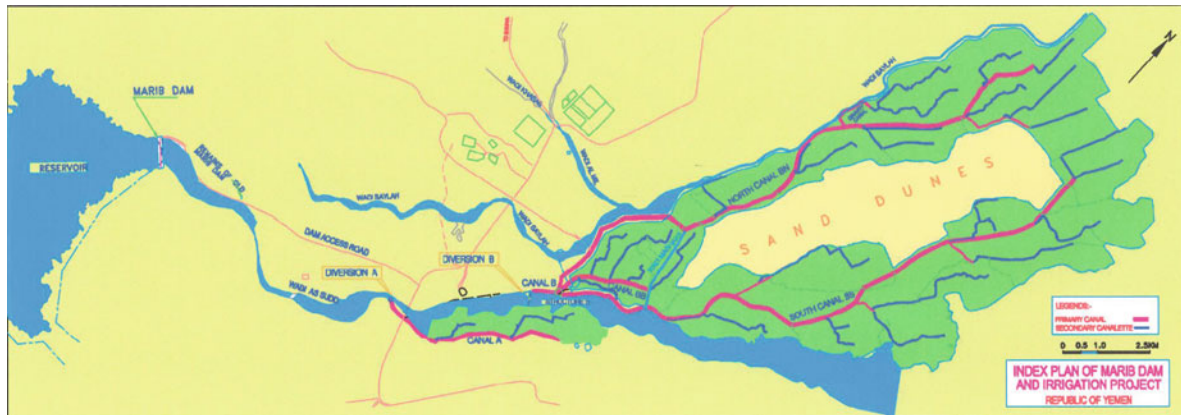
Condition of the irrigation system

The occurrences of high frequency of rainfall in the year of 1994 and 1996 caused a flash flood through various wadis (wide-bedded rivers) which damaged the crops, canals, and canal structures severely. The flood washed out a considerable reach of BN canal and its regulation structures away (Figure 4).

As the system was incomplete and inoperative since 1990, a large stretch of canal system and the control structures became buried under sand due to excessive sand storms and movement of the sand dunes (Figure 5).

The culverts across the main canal also became inaccessible in most cases due to the erosion of approach ramps, and local people have made crossing over the canal possible by filling it with sand.

The extent of damages witnessed in the 1996 flood was a serious concern to the country. The Government of the Republic of Yemen initiated action for the study of flood protection required for taking up appropriate measure. Accordingly, in 1998, appropriate flood protection measures were taken up for the main canal



Marib Dam and irrigation project, Figure 3 Plan of the Marib irrigation scheme, showing location of the main dam, diversion structures A and B, and main canals A, B, BN, BB, and BS.



Marib Dam and irrigation project, Figure 4 Flood damage to canal network.

system: construction of secondary canal system, repairing works of primary canals damaged during 1996 floods, and construction of feeder roads along the main canals as outstanding works of Phase II.

Study of the rehabilitation of the canal system was completed in 1999, and the construction work was completed in 2003.

Project area

The dam is constructed across the main river, Wadi Abida. The length of the reservoir is 10 km, and its area is 30.5 sq km. The downstream of river Wadi Abida after the dam is called Wadi As Sudd. After aerial survey, depending upon the land tenure, land use, fertility of land, and tribal boundary, a total command area of 7,400 ha has been selected to bring under direct irrigation from the scheme including 405 ha for canal A at the left bank of Wadi As Sudd, 3,971 ha for BS canal at the right bank of Wadi As Sudd, 3,071 ha for BN canal at the right bank of Wadi Sailah,

and 736 ha of area for BB canal between the command area of BS canal and BN canal. The major crops of the area are wheat, sorghum, lucerne, citrus, vegetables like tomato and potato, and watermelon. Only 35% of the planned command is presently being cultivated by the help of pump irrigation.

Hydrology

Though the flood of Wadi Abida is arrested by the main dam and the excess water in Wadi As Sudd is controlled by diversion structures A and B, the flood of Wadi Sailah originating from eastern hill of the project area and flowing along the left command boundary of BN canal is totally uncontrolled and beyond the managing capability of local farmers. Wadi Sailah and its tributaries drain off about 300 sq km and causes disaster in 5–10-year-frequency floods. Though the rainfall in the project area is scanty, the mean annual rainfall is 100 mm. Rain in hilly zones generates flash flood through these wadis.

The irrigation system

Main dam

The new Marib dam (Figure 6) is a zoned earth fill dam, 38 m in height and having a 780-m-long crest with central impervious core functioning as positive cutoff in the alluvial foundation and shell zones on either side. It has a storage capacity of 400 million cubic meters. Curtain grout has been provided in the abutments on both the flanks of the wadi. The reservoir area of the dam is 30.5 sq km. From the bottom sluice of Marib dam, 35 cumec water is to be released in to Wadi As Sudd to feed irrigation network for providing irrigation water to 7,400 ha of the command area.

Diversion structures

About 11 km downstream of the main dam, diversion A structure has been constructed across Wadi As Sudd to control the flow of water to feed canal A. It is a concrete “ogge” shaped spillway section with head works at its right side (Figure 7).



Marib Dam and irrigation project, Figure 5 Buried canal structure under sand dune.



Marib Dam and irrigation project, Figure 6 The new Marib Dam.

About 5 km further downstream of diversion A, diversion B structure has been constructed across Wadi As Sudd to regulate the flow requirement in feeder canal B. This is also a concrete “ogge” shaped spillway section with head works at its left side.

Main canal system

Canal A takes off from the head works of diversion A. The capacity of canal A is 840 l/s. The 4.8-km-long canal is constructed to irrigate 405 ha of command area.

One-kilometer-long canal B takes off from the head works of diversion B. The capacity of the feeder canal B is 15 cumec. At the tail end of canal B, distribution structure B is constructed to trifurcate canal B in three main canals – BS, BN, and BB canals. The structure controls and distributes water to 15.75-km-long BN canal,



Marib Dam and irrigation project, Figure 7 Diversion Structure A.

3.75-km-long BB canal, and 16.8-km-long BS canal. The distribution of water is achieved by a combination of NEYRTEC-type distributor modules (product of Alstom). Each module consists of series of slide gates, which control the flow of water. The upstream water level is kept nearly constant. Design capacity of BN canal is 6.5 cumec to irrigate 3,071 ha area. The capacity of BS canal is 7 cumec to irrigate 3,190 ha area. Capacity of BB canal is 1.5 cumec, and its command is 736 ha.

The main canal system is a completely concrete-lined canal of trapezoidal cross section (Figure 8). The steeper slope of the ground has been negotiated by providing numbers of drop structures in the main canal system. The head of the main canal system is automatically regulated by the combination of AMIL gates and CHO gates. Automatic siphon units have been introduced at the upstream of the AMIL gate to avoid any malfunction due to excess water in the main canal. From this main canal, few branch canals are also designed to supply the water at the head of the secondary canal where command area is far from the main canal.

Secondary canal system

Eighty-eight-kilometer-long secondary canal system is developed to supply water in 22 sectors – each having an area varying from 100 to 460 ha. From the secondary canalette, turnout structures are designed to serve water at tertiary channels for different blocks varying from 10 to 30 ha. After analyzing crop-water requirement, the required design discharge is derived as 2.2 l/s/ha.

To avoid the seepage loss, minimize the land acquisition, and for easy as well as rapid construction in sandy soil, three types of semicircular reinforced concrete precast units (called canalette) of standard length of 5 m and 2.5 m have been used depending upon the discharge. These precast units are placed over a combination of precast monoblock, pier, and standard saddle support over Class C concrete foundation under the ground level (Figure 9). To provide expansion, joint elastic strips have been used between the saddles and canalette, and



Marib Dam and irrigation project, Figure 8 View of main canal.



Marib Dam and irrigation project, Figure 10 Culvert across secondary canalette.



Marib Dam and irrigation project, Figure 9 View of secondary canalette.

bituminous sealant has been provided between the gaps of two canalettes. The slope of the secondary canal is fixed in such a manner that the design velocity through the canalette will be always lower than its critical velocity. The whole system is designed by an interesting computer program developed by the consultants for quick and appropriate installation. The precast units and its foundations are designed for impact and seismic effect. For all types of precast units, concrete was poured in the steel forms and simultaneously vibrated with vibration table for a period of 5–8 min. After 2 h of steam curing at a temperature of 70°C, the outer form was removed, and the inner form was removed after 3 h of additional steam curing. After removal of forms, all the precast units were placed in curing pool for 7 days.

The elevated secondary canalettes act as branch canal. At the turnout point of secondary canalette, double baffles XX2-type NEYRTEC modules (product of Alstom) of 10–60-l/s capacity have been installed for steady supply of water in tertiary channels, depending upon the size of the blocks. The discharge can be controlled by raising or lowering the steel flaps, provided in the modules. Individual fields will be irrigated through the earthen field channel taken off from the tertiary outlets. This earthen channel would be constructed by the local landowners as per their planning. Numbers of slab culvert have been provided at the existing roads to cross the secondary canalettes (Figure 10).

Road network

Side by side with the agricultural development, the project authority made an ambitious plan to connect the adjoining villages to the main city market by feeder roads to facilitate transportation of agricultural products to the cooperative market. The feeder road is of asphalt, 40-km-long and 6-m-wide asphalt feeder along the main canals, and a 70-km-long gravel-surfaced road along the secondary canalette joining the villages has been taken up (Figure 11).

Flood protection scheme

As the flash flood is the major reason for the disaster of the canal system, special care has been taken for the flood protection scheme. A 25-km-long flood protection embankment is being constructed to protect the command boundary of BN canals and the adjacent villages, which are vulnerable to flood from the flood of Wadi Sailah. The protection scheme is designed for 50-year-frequency flood of magnitude of about 700 cumec. The toe of the embankment is protected with 1-m-thick and 5-m-wide



Marib Dam and irrigation project, Figure 11 Road network.



Marib Dam and irrigation project, Figure 12 View of flood protection embankment.

wire mesh gabion boxes, and the waterside slope is protected with 50-cm-thick hand-placed stone pitching over filter. The top of the embankment is also protected with gravel pitching (Figure 12). Controlled pipe outlet structure has been provided to the riverside agricultural land through the embankment to facilitate conventional spate irrigation during rain. Remodeling of diversion A and diversion B is also being done to increase their spilling capacity.

Sand dune combating scheme

Considerable stretch of the main canal system passes through the sand dune prone areas. Excessive sand storms and movement of the dunes have affected the system badly. To combat the windblown sand affecting the function of canal system, the following treatment is being carried out (Figure 13):

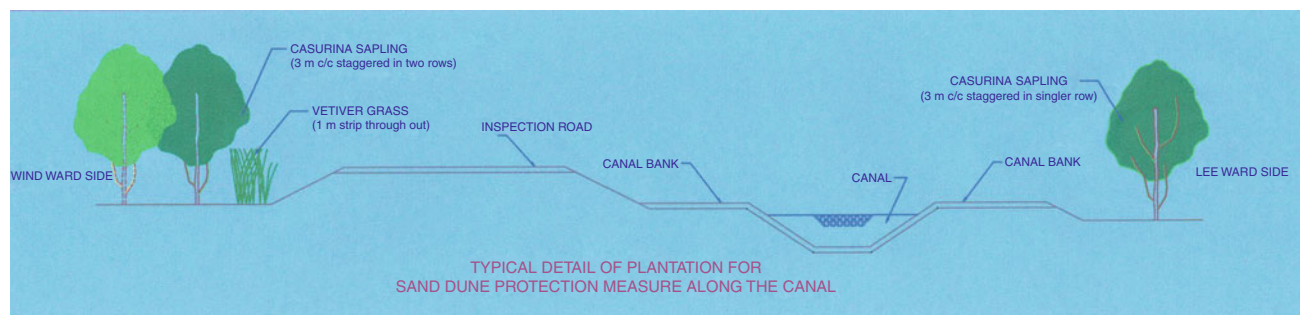
- Planting of two rows of (staggered) Casuarina sapling along the canal bank in the windward side.
- Planting of single rows of Casuarina sapling along the canal bank in the leeward side.
- In the worst sand-blown areas, plantation of additional strips of vetiver grass.

Cost of the project

The cost of the Phase I work including dam and main canal system was completed in US\$ 75 million. The budgeted cost of Phase II works including production and installation of secondary canalette was US\$ 22 million. Though the production of precast canalette was over, only 6% of the secondary canalette was installed. The cost of present execution of outstanding works including repair of canal, installation of secondary canalettes and feeder roads, and flood protection scheme is US\$ 23 million.

Benefit

On completion of the project 65% additional area in the form of barren desert would be irrigated through the canal system. After recharge of the aquifer, the raised water table improved pumping. Farmers are now able to use the floodwater from the wadi in a controlled manner.



Marib Dam and irrigation project, Figure 13 Typical detail of plantation to combat sand dune.

The agricultural production will suffice internal demand and increase export possibility. The development of road network added the importance of the area and the rapid development of shops and hotels. Extensive training by the consultants was given after completion for the operation and maintenance of the project.

Challenges

Here in Marib, the relation between families and tribal groupings is complex, being influenced by blood relationship and dominated by Islamic and pre-Islamic laws and traditions. The habit to take revenge has been passed on throughout generations and still aggravates the social situation today. Till date, people prefer to obey the tribal laws rather than Government rules. At the beginning of the project, people had a hostile attitude about this Government endeavor. But after repeated campaigning about the benefit of the project, people are now in favor of the project. Repeated changes in alignment due to frequent disputes over land boundaries, demands for compensation from Phase I and for Phase II, and old unresolved tribal problems caused several isolated stoppages in the project and delayed the progress of work. Marib dam is the largest dam in Yemen with its glorious history. Completion of the Marib dam and irrigation project in the adverse climatic and social condition is a major challenge to the Government of Yemen and Abu Dhabi Fund for Development. It has created an example to the world as a “Wonder in the Desert.”

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Cross-references

[Arab Region, Lakes and Reservoirs](#)

MASS CURVE AND RESERVOIR DESIGN

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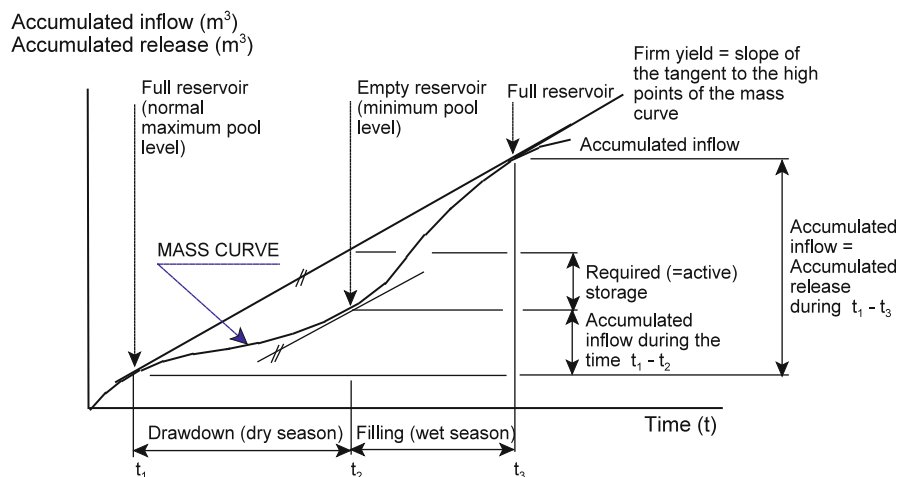
Description

A reservoir is essentially a lake with a dam in its outlet where the flow can be controlled. The reservoir can be either a natural lake or created by the construction of a dam in a river.

The purpose of a reservoir is to store water during periods of high flow, for example, a rainy season or a snow-melting period, and for use during periods of low flow or droughts, for example, for water supply, irrigation, hydroelectric power, or a combination thereof.

The maximum level to which the reservoir surface is allowed to rise during normal operating conditions is called *normal maximum pool level*. The lowest elevation to which the reservoir surface is allowed to be drawn during normal operating conditions is called *the minimum pool level*. The volume retained between these levels represents the water volume that can be used and is called *active (useful) storage*. The volume below the minimum pool level can normally not be used and is called *dead storage*.

The maximum amount of water that can be released from a reservoir during a dry period, *the firm (safe) yield*, can be determined a mass curve (Rippl diagram), where the accumulated natural inflow adjusted for evaporation losses is plotted as a function of time as shown in the [Figure 1](#).



Mass Curve and Reservoir Design, Figure 1 Determination of the firm yield and required storage with a mass curve.

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Cross-references

Dams, Flood Protection, and Risk
 Hydrological Sizing of Water Supply Reservoirs
 Large Dams, Statistics and Critical Review

MEMPHREMAGOG, LAKE

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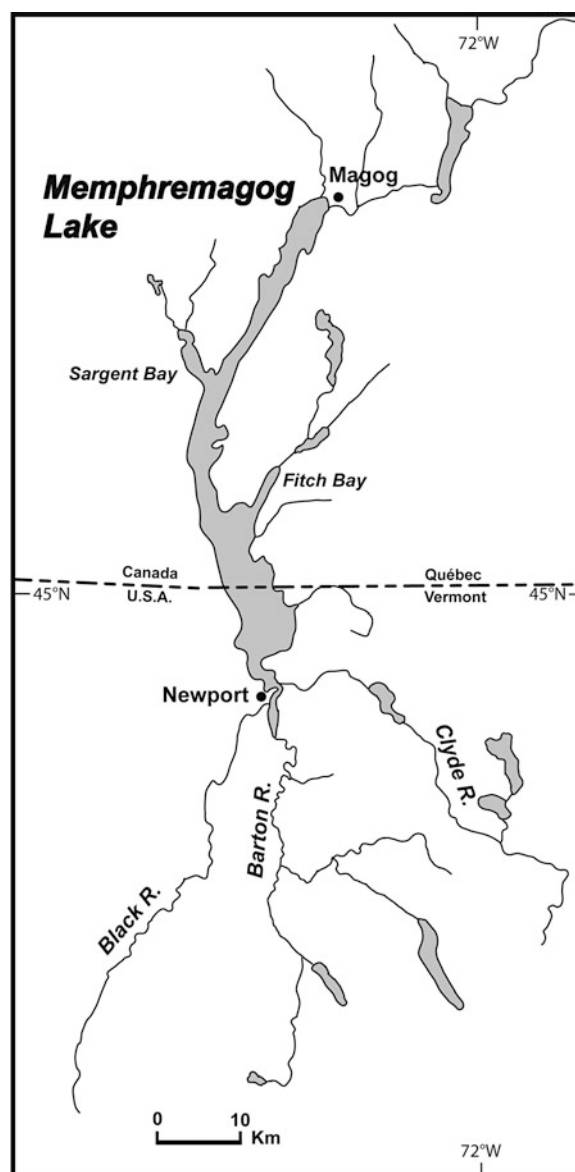
Location

Lake Memphremagog (Figure 1) is an international lake across the Canada–USA border (Figure 2), with about three quarters of the 102 km² lake's surface area in the region of Québec called "Estrie" or "Eastern Townships" (Canada) and the remaining part in Vermont (USA). The lake is oriented north to south, from Newport (Vermont) to Magog (Québec). It is about 43 km long and



Memphremagog, Lake, Figure 1 Aerial view of Lake Memphremagog, from the Northwest, at its outlet at Magog (coll. J.-M. M. Dubois).

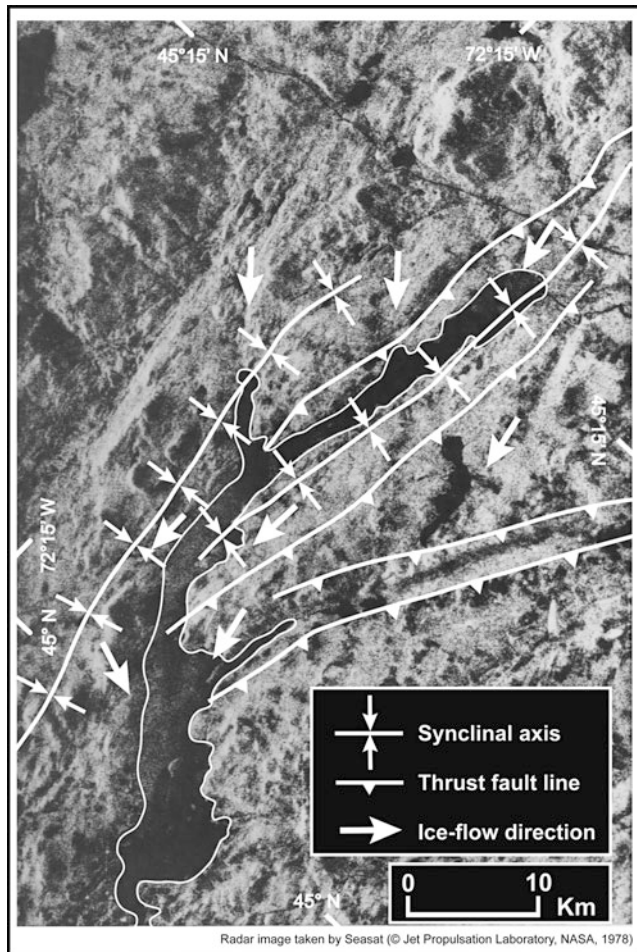
1.5–5 km wide. Its shoreline measures about 120 km long. The lake is relatively deep, with a maximum water depth of 117 m, which measured just at the bottom of Mount Owl's Head. It has three distinct basins: one deep central basin, and two shallower north and south basins. It counts about 20 islands; the largest one being the Province Island, which is located on the international border. The lake watershed is less than 1,800 km², with about three quarters located in Vermont. In Vermont, three rivers (the Black, Barton, and Clyde rivers) reach the lake at its extreme south end. The outlet of the lake is the Mago River, which flows northeast and reaches the Saint-François River, at Sherbrooke. This river is an important south tributary of the St. Lawrence River.



Memphremagog, Lake, Figure 2 Map of the Lake Memphremagog basin.

Origin and evolution

The shape of Lake Memphremagog is similar to an elongated finger or to a boomerang, with two excrescences: Fitch Bay and Sargent Bay. This shape is related to an elongated basin between the Sutton Mountains, on the West, and the Upper Appalachian Plateau, which is a region of rolling hills and valleys, on the East (Dubois, 1989). It is mainly due to three major past events: the Appalachian orogen, the Quaternary glaciations, and the last ice retreat. Firstly, the lake is located in the Appalachian terrains, which are a series of mountains and highlands, stretching along the eastern portion of the North America continent. The Appalachian orogen was the result of the collision of two large supercontinents (the Laurentia and the Gondwana) and the Paleozoic closure of the Iapetus Ocean. This geologic event is characterized by uplift and folding of seafloor deposits, and by intrusion of volcanic and plutonic magmas. The configuration of Lake Memphremagog mostly follows these folded and faulted



Memphremagog, Lake, Figure 3 Seasat image of the Lake Memphremagog area, showing its main geological and glacial features (Courtesy of NASA).

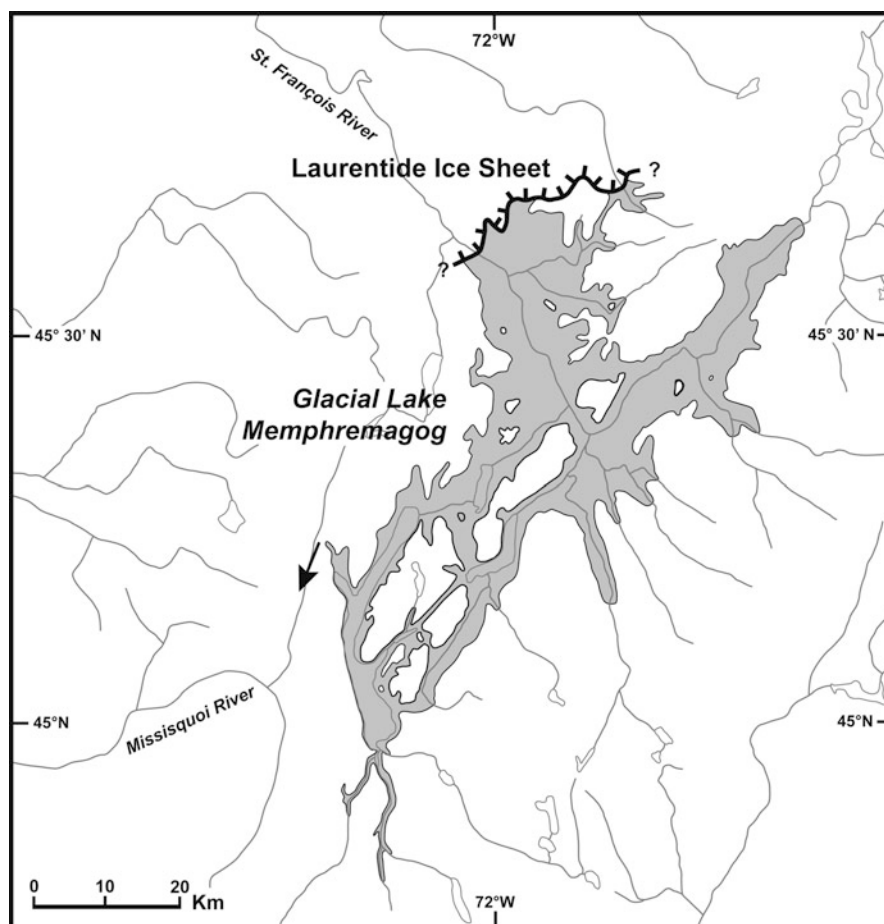
strata. The northern half of the lake and the Sargent Bay occupy the bottom of a syncline, while the Fitch Bay follows the position of a thrust fault (Figure 3).

Second, the basin of Lake Memphremagog has been slightly remodeled by glaciers during the Quaternary glaciations. At that time, ice covered several times this portion of North America. During ice advances and retreats, glaciers dragged rocks and soil beneath them, which resulted to a down smoothing of the mountains along the west side and a deepening of preexisting valleys at the lake site (Sangree, 1953). Directions of ice flow follow the axis of the lake (Figure 3), supporting the hypothesis of glacial gouging of a preexisting valley. Moreover, the lake floor is also covered by more than 100 m of unconsolidated postglacial and probably preglacial sediments (Turgeon et al., 2003).

Third, the actual lake is the relic of a late-glacial ice-dammed lake. During the last deglaciation, a Laurentide ice front retreated northwestward across the region. It has blocked the normal drainage and impounded a proglacial water body in the current basin of Lake Memphremagog. Hitchcock (1895) first recognized the existence of this ice-dammed lake, and Hitchcock (1908) called it "Glacial Lake Memphremagog." More recent studies (McDonald, 1968; Stewart and MacClintock, 1969; Boissonnault and Gwyn, 1983; LaRocque et al., 2003) determined at least eight successive glaciolacustrine levels (375 m, 355–360 m, 350 m, 320–325 m, 305 m, 270–275 m, 265 m, and 235–270 m) for that lake. The lake had its maximum extent during the lowest level, known as the Sherbrooke Phase (Figure 4). It was drained westwards, via the Lac Nick spillway and the Missisquoi River, into Glacial Lake Vermont, another ice-dammed lake which occupied the basin of Lake Champlain, prior to the Champlain Sea (Parent and Occhietti, 1999). Just after the maximum extent of Glacial Lake Memphremagog, at about 12,200 years BP, the water level rapidly fell of about 40 m (Parent and Occhietti, 1999). This event marked the end of Glacial Lake Memphremagog and the beginning of the residual Lake Memphremagog. Since that time, the water level in the Lake Memphremagog basin has lowered gradually, with the gradual incision of the lake outlet. Since the end of the eighteenth century, the lake level is artificially controlled by a dam which was built on the Magog River for hydraulic power production. The current dam was built in 1920 just inside the town of Magog (Québec) for the electrical power production and maintains the lake level at an elevation of 208 m above sea level.

History

Since the first human settlements in the area after the last glaciation, native peoples always used Lake Memphremagog as a canoe route. They also sparsely occupied the lakeshore because the lake was a source of foods and drinkable water. The native past of the lake is recalled by several location names, like Indian Point, Magog, and Wigwam Point. The name of the lake itself,



Memphremagog, Lake, Figure 4 Maximum extension of Glacial Lake Memphremagog (Modified from Parent and Occhietti, 1999 and LaRocque et al., 2003).

Memphremagog, is an Abenaki word meaning “*great water plane*” (Commission de Toponymie du Québec, 1994). The first European settlements were established in the region at the end of the eighteenth century, after the American Revolution. At that time, part of the British peoples, who stayed loyal to the British Crown, left New England for Canada through the lake. These *United Empire Loyalists* settled in Newport (Vermont) in 1793 and at Gibraltar Point (which is now located in Bolton Township, Québec) in 1794. In 1797, the British Crown established for these Loyalists the two first townships in Canada (Bolton and Potton) on the west side of the lake. By mid-1800s, the region became one of the first touristic regions of Québec and the lake became a vacation resort. Tourism dramatically increased when the railroad reached both ends of the lake (Gagnon, 2003). First-class hotels were built along the lakeshore for tourist accommodation. Two steamboats (*Mountain Maid* in 1850 and *Lady of the Lake* in 1867) were used to travel from one end of the lake to the other. Since 1857, the summit of Mount Owl’s Head on the west shore is the site of initiation for the Freemasonry Golden Lodge of Stanstead. It is the only open air

lodge in North America, which is still used each summer solstice. After 1850, the development of the railroad and the forestry industry allowed the establishment of French Canadians. They were the majority in population by the beginning of the twentieth century. Presently, the area surrounding the lake is covered mostly by forest lands, except in Vermont where it is largely dominated by agricultural fields. The area has significant summer and winter recreation activities both in Vermont and in Québec.

Water quality

The Lake Memphremagog and its watershed support a diversity of plant, fish, and wildlife species habitats. However, like many other freshwater bodies, this lake is faced with accumulation of phosphorus, chlorophyll, sediments, and other pollutants, affecting water quality. This degradation is mainly shown by a premature aging of the lake, which is currently in a mesotrophic stage, especially in low depth zones. This is mainly the case at the south end of the lake, where three rivers provide the primary input of nutrients into the lake. By contrast, the central and north parts of the lake remain oligotrophic. The lake area is also

facing with invasion by nonnative species, like populations of Eurasian water milfoil and possible lake infestations by zebra mussels.

Since the 1970s, a cooperative effort between Vermont and Quebec has been made to improve this natural resource and to protect it against polluting effects of direct discharges into the lake and its tributaries. First, an international commission was initiated to manage the water level of the lake. In 1989, a working group was established to identify the principal causes of lake management problems and to take actions for preserving its environment. The commission produced a final report in 1993 and a Québec/Vermont steering committee was established to apply its recommendations. In 1994, the Lake Memphremagog Watershed Association was created to bring together citizens interested in lake and river issues in the lake basin. Since 2003, this working group is interested in all the watershed of Lake Memphremagog (Simoneau, 2004). Currently, more attention is given for addressing sources of diffuse pollution.

Myths

Several myths exist about Lake Memphremagog, among them the supposed existence of an aquatic monster, called “Memphré” (Meurger, 1982). It is considered as a 13-m inland sea serpent. This underwater lake-dwelling creature would be a cousin of the famous “Nessie,” from the Loch Ness (Scotland), and “Ogopogo,” from Lake Okanagan (Central British Columbia, Canada). The apparition of Memphré was first reported in 1816 as the native myth of the sea serpent “Anaconda,” and since then, more than 500 reports by different peoples have been recorded. However, it is still not possible to demonstrate the existence of Memphré in the lake, but the Vermont Legislature adopted an Act (number J.H.R. 19) for the protection of “Memphré.” For studying the “Memphré,” the *International Society of Dracontology* (<http://www.memphre.com>) was founded in Magog in 1986 by the “father of Memphré,” Jacques Boisvert, who died at the beginning of 2006. The mother of “Memphré” is Barbara Malloy from Newport.

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Cross-references

[Classification of Lakes from Origin Processes](#)
[Great Lakes, North America](#)
[Lake Monster](#)
[Lakes on Earth, Different Types](#)
[Origin of Lakes and Their Physical Characteristics](#)
[Water Quality in Lakes and Reservoirs](#)

MEROMICTIC LAKES

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Classification and terminology

Lakes are classified based on the seasonal thermal conditions that determine stratification and mixing processes. These conditions are affected by changes in lake morphometry (depth, surface area), drainage basin morphometry (area, topography, climate), and dissolved and suspended solids in their waters (vertically, seasonally, annually). Lakes where water circulates throughout the entire water column are called *holomictic* lakes and are by far the most common. Usually, this occurs at least twice annually in temperate regions, with such lakes being called *dimictic*. Lakes that do not undergo complete circulation are referred to as *meromictic* lakes and occur when salinity or turbidity gradients set up concentration profiles

with enough density difference to bring about stability of their lower layers (Hutchinson, 1957; Wetzel, 2001). This stability isolates the bottom water from the surface water, and terminology has been developed to describe these zones within these lakes (Findenegg, 1937). The upper zone that undergoes periodic (often twice a year) circulation is called the *mixolimnion* and the lower zone is called the *monimolimnion*. These zones are separated by a very steep but usually relatively thin chemical and hence density gradient called a *chemocline*.

Meromictic lakes can be classified based on the conditions and processes that bring the saline and freshwaters together in the same basin to set up sharp density stratification conditions. *Ectogenic* meromixis often occurs in coastal areas where seawater due to a storm event or extreme tidal activity intrudes onto a freshwater low salinity/density layer. Seawater in fiord areas can also be trapped as glaciers melt and the land surface rebounds with subsequent freshwater runoff setting up the conditions for meromixis. Examples of this kind of meromixis include Nitinat and Sakinaw Lakes in British Columbia (Northcote and Johnson, 1964; Northcote et al., 1964.) and Lake Tokke in Norway (Strøm, 1955). *Crenogenic* meromixis occurs when saline springs discharge dense water onto a freshwater lake depression setting up density stabilizing conditions. Examples of crenogenic meromictic lakes are Ulmener Maar in Germany (Stewart and Hollan, 1975) and Lake Sinmiyo in Japan (Yoshimura, 1937). *Biogenic* meromixis results from an accumulation of higher dissolved solids as a result of decomposition processes in the bottom of the lake that gradually stabilizes the bottom layer and prevents complete circulation. Examples of biogenic meromictic lakes include Lake Mary, Wisconsin (Weimer and Lee, 1973), as well as Wörthersee and Millstättersee in Austria (Hutchinson, 1957). Mahoney Lake in British Columbia could also be classified as a partially biogenic meromictic lake, but surface runoff from saline rich geological formations in the watershed with no lake outflow and evaporative concentration also have helped to establish meromixis (Northcote and Hall, 1983). Yellow Lake, also in British Columbia, can also be classified as biogenic, but the lake lies in a remnant glacial meltwater channel and its morphometric features (deep, narrow, and protected from high winds) have helped to set up meromixis in this lake (Northcote and Halsey, 1969).

No classification system for meromixis is perfect. More recently, Walker and Likens (1975) proposed a modified classification that only has two classes of meromixis, namely ectogenic and endogenic, and then segregates lakes under these classes into several types based on the physical-chemical process that helps to create the stability. Anderson et al. (1985) used this classification system for a comprehensive list of North American meromictic lakes with varved sediments.

Some lakes may be classified as *partially meromictic*. This can happen where there are two basins in the lake, and usually the deeper basin sets up meromixis such

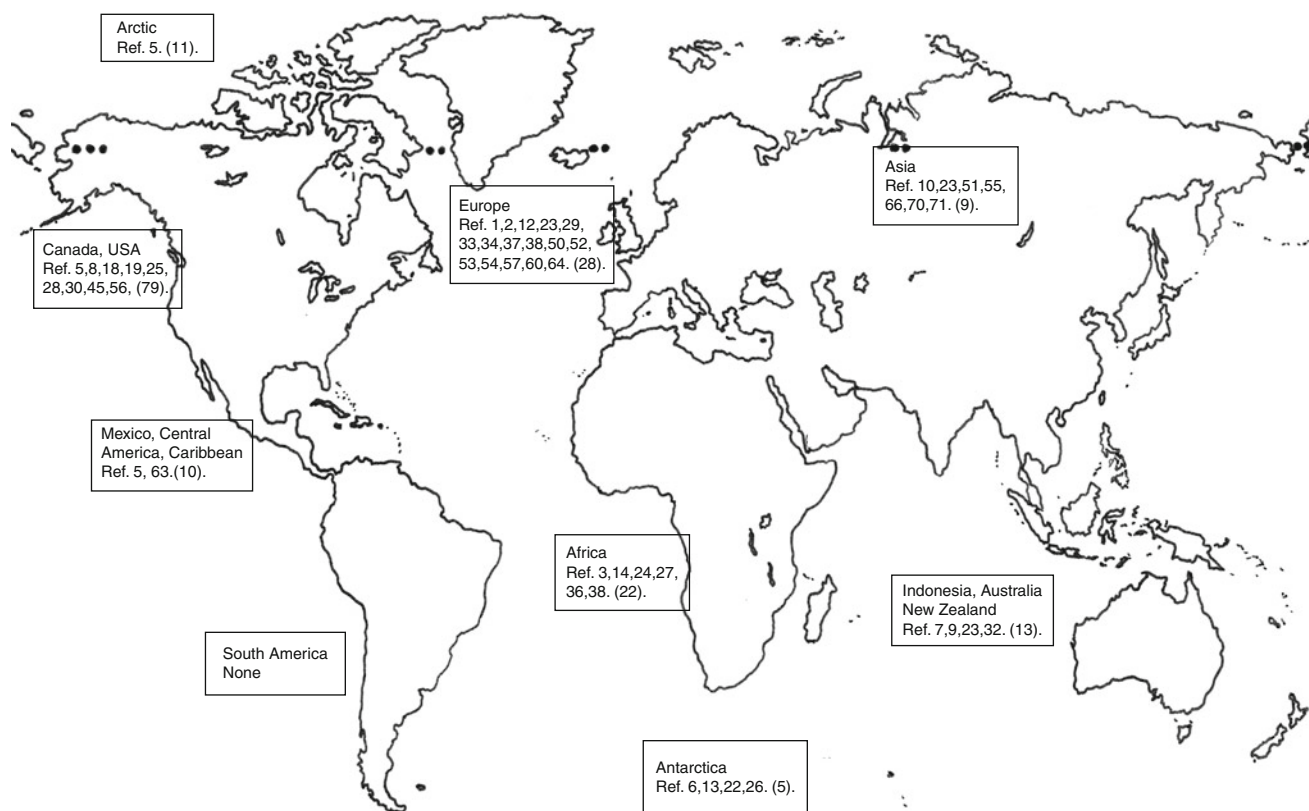
as what occurs in Baptista and Amisk Lakes in Alberta (Kira, 1995). Partial meromixis may also occur seasonally where the influx of freshwater in the spring due to snow-melt causes a density difference that isolates the lower water for part of the season until evaporation or wind mixing breaks down the density stratification.

Geographic distribution

We attempted a compilation of a list providing reference to most of the meromictic lakes that have been identified and/or studied in the world. These lakes have been segregated globally into nine regions (Figure 1). The comprehensive listing of North American lakes with varved sediments provided by Anderson et al. (1985) identifies 88 meromictic lakes, and the reader is referred to this reference and its literature citations. Our geographic summary of meromictic lakes indicates that most identified meromictic lakes occur in North America and Europe. The meromictic lakes in Africa are largely deep ones localized in the rift valleys or in remains of volcanic cones. Although there are numerous saline lakes in Australia, the arid conditions on that continent generally prevents establishment of meromixis. Only four meromictic lakes have been reported on that continent with three of these located in Tasmania (Bayly and Williams, 1973; Croome and Tyler, 1984). Polar meromictic lakes are likely formed by the freeze-out of salts helping to establish a fresher surface layer. No literature could be found on meromictic lakes in South America. The 17 chapters on limnology in Brazil (Tundisi et al., 1995) make no mention of meromixis there, especially that by Henry (1995) covering the thermal structure of 16 widespread lakes and reservoirs in that large part of South America, nor in over 100 lakes in the Rio Doce valley, Brazil (Tundisi and Saijo, 1997). One might expect to find a few meromictic lakes in parts of Chile and Argentina.

Meromixis and thermal stratification

The saline stability of meromictic lakes leads to some interesting thermal conditions in their vertical profiles that can have a significant influence on physical and biological processes. The bottom monimolimnion of many meromictic lakes is relatively warm and this temperature can be very stable over the seasons and over many years. The bottom waters of Mahoney Lake in British Columbia, Canada, have been constantly between 12°C and 15°C for the past 30 years. Solar energy can be trapped under less saline surface water, and temperatures in excess of 50°C have been recorded in the chemocline of shallow Hot Lake in Washington (Anderson, 1958). Recently, Northcote and Hall (2000) introduced the term “bimeromixis” when periodic vernal influx of freshwater caused the formation of a secondary chemocline in the mixolimnion with temperatures up to 30°C in May at 2–4 m in Mahoney Lake. In this area of secondary stability, heterotrophic activity was stimulated with a high uptake of radioactive solutes (Hall and Northcote, 1990). This bimeromixis also intensified primary production processes with dissolved



Meromictic Lakes, Figure 1 Location and reference to identified meromictic lakes of the world (the numbers in the boxes of each region are keyed to the alphabetic reference list which identifies the specific lake and its location in *bold* letters; the number in brackets gives the total number of meromictic lakes identified for that region; the filled circles delineate 66°N latitude to show the region of the Arctic).

oxygen concentrations reaching 25–30 mg/l (up to 300% supersaturation) during the summer period (Hall and Northcote, 2002). This biological stimulation is most likely attributable to an influx of nutrients from spring run-off and the flooding of the littoral zone by a higher lake level, as well as trapping and recycling of nutrients associated with detrital material that collects at this stable boundary.

Meromictic effects on lake geochemistry and microbial processes

The long-term stratification of meromictic lakes with isolation of monimolimnion waters from circulation sets up redox conditions that influence decomposition and phototrophic carbon fixation processes throughout the water column. The monimolimnion becomes highly anoxic in meromictic lakes, and high concentrations of hydrogen sulfide can accumulate when sulfate-reducing anaerobic bacteria (*Desulfovibrio*, *Desulfotomaculum*) use sulfate as an electron acceptor during heterotrophic decomposition of organic matter (Wetzel, 2001; Sorokin, 1970). The chemocline with its steep chemical gradient creates a sharp redox gradient where oxygen concentrations can rapidly decrease to zero and several 100 mg/l

of hydrogen sulfide can occur over a depth interval of 20 cm (Overmann et al., 1991). If light energy penetrates to the chemocline, in the presence of the hydrogen sulfide which serves as an electron donor, dense plates of phototrophic purple sulfur bacteria can develop (Northcote and Hall, 1983; Overmann et al., 1991). This very small layer can contribute to a significant percentage (17–66%) of the autotrophic carbon fixation in the water column (Hall and Northcote, 1990). Green phototrophic bacteria (*Chlorobacteriaceae*) can also develop at these stratified boundaries, but they are not usually as dense as the purple sulfur bacteria (*Thiorhodaceae*) (Wetzel, 2001).

Observations of sulfur bacteria in the guts of copepods (*Diaptomus connexus*) and subsequent studies of stable sulfur isotopes and ¹⁴C food chain studies demonstrated that these aerobic organisms could obtain energy fixed in the anoxic environment by the anaerobic purple sulfur bacteria as the copepods made excursions into the chemocline to graze on the bacteria (Overmann et al., 1999a). Water level changes can make the stability of the chemocline vulnerable and along with the development of buoyancy by the purple sulfur bacteria can disperse bacterial clumps into the mixolimnion, grazed upon by ciliates and invertebrates (Overmann et al., 1999b).

When this occurs, the shoreline of lakes is often coated with a film of purple sulfur bacteria. For more detailed studies on the seasonal dynamics and long-term changes in meromictic lakes, the reader is referred to the extensive literature published on Längsee (Austria), Big Soda Lake (Nevada), Mono Lake (California), and Mahoney Lake (British Columbia).

Sediments in meromictic lakes

The anoxic conditions in the monimolimnion exclude benthic invertebrates from much of the sediment. This prevents sediment bioturbation or disturbance, and often the seasonal production and precipitation processes create distinct annual layers, called varves, which are easily visible in a sediment core (Lowe et al., 1997). The sediment cores allow detailed sedimentological studies to be conducted which can provide long-term information on development of salinity in the lake. Historic lake salinity changes in Mahoney Lake have been inferred from the identification of diatom and chironomid remains in the sediments (Heinrichs et al., 1997). Pigment preservation in anoxic sediments helps to determine how long and when purple sulfur bacteria have been present in a lake. In the example of Mahoney Lake, the sediment profile of the carotenoid, okenone, which is the pink accessory pigment of *Amoebobacter purpureus*, indicates that the purple sulfur bacteria have been in the lake for approximately 9,000 years and that meromixis may have existed in this lake for a similar period (Overmann et al., 1993). Algal pigments can help determine how the phytoplankton community has changed historically and how important it is in lake primary production compared to that of phototrophic purple sulfur bacteria.

Meromixis in the past, present, and future

Information on climate change since last glaciation can also be studied by investigating the extent of chemical precipitation events and the chemistry of the elements in the core, and the long-term presence or changes in the degree as well as type of meromixis (Lowe et al., 1997; Hall and Northcote, 2000).

Coastal and near-coastal lakes may trap seawater for short or long periods of time depending on the multiple effects of deglacial isostatic rebound and higher sea levels. For example, Powell Lake lying some 60 m above present sea level contains in its bottom waters a salinity of 18‰ which entered the lake basin some 13,000 years ago when coastal waters were heavily diluted by massive meltwater dilution resulting from deglaciation (Williams et al., 1961). In contrast, present-day Nitinat Lake on the west coast of Vancouver Island is partially meromictic, containing at depths below 3 m saline water close to that of the coastal Pacific Ocean into which it drains from its short (<2-km) outlet river. At high tide levels combined with strong onshore winds, nearby coastal seawater may enter the lake basin setting up strong meromictic conditions (Northcote et al., 1964). Just over 100 km northeast of Nitinat Lake lies the coastal mainland lake Sakinaw,

some 3 m above present sea level, and offering a clear example of present-day ectogenic meromixis (Northcote and Johnson, 1964). Sakinaw Lake is two-basined, its main portion having a maximum depth of 140 m and its smaller northeastern basin a 40-m maximum depth, and that of the nearby Ruby Lake 100 m. Only the lower basin of Sakinaw Lake is meromictic now, with its upper basin and that of Ruby Lake being holomictic. Probably in the recent geological past all three basins of the Sakinaw–Ruby chain were filled with coastal seawater, a feature that should be checked out by deepwater coring.

Another presently meromictic lake (Mahoney) lies in South Central British Columbia (Northcote and Halsey, 1969) where a 5.45-m-long sediment core gave its age as over 11,000 year BP (Lowe et al., 1997) and from which Holocene fluctuations in its meromixis, water level, and depth, along with local climatic changes, could be inferred. Meromixis developed in the lake about 9,000 year BP and has been episodically meromictic for about half of the time since then when Holocene temperatures and aridity were at a maximum in western Canada and the northwestern United States. Outstanding features of the Mahoney Lake record are the rapidity and high frequency of inferred climatic changes (Lowe et al., 1997) along with longer periods of relative stability, following patterns called climatic “flickering” – short-term oscillations between distinct climatic states (Lehman, 1993; Taylor et al., 1993). The prediction and assessment of future global environmental change on lake morphometry, inflow discharge, ice-free period, and water temperature have been reviewed for British Columbia in general and South Central B.C. in particular (Northcote, 1992).

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Cross-references

Antarctic Lakes
Arctic Lakes
Dead Sea
Great Salt Lake
Lakes on Earth, Different Types
Paleolimnology
Stratification in Lakes
Tanganyika Lake, Modeling the Eco-hydrodynamics
Thermal Regime of Lakes

MICROORGANISMS IN LAKES AND RESERVOIRS

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Introduction

Although invisible to the naked eye, bacteria in the form of microorganisms are present in all water bodies, particularly in the sediments of lakes, reservoirs, and rivers. These organisms have a key role in the nitrogen cycle and are involved in biological processes. Bacteria play the central role in natural self-purification by decomposing organic matter into its inorganic components which are then recycled. *Pathogenic organisms, bacteria, and viruses* are of particular concern in lakes

and reservoirs used as a source of potable supply or for bathing. In the case of potable supplies, modern water treatment processes, including disinfection, ensure that sources are well protected and that any pathogens present are removed by filtration or killed.

Cyanobacteria are an important group of plants often appearing a dominant part of the phytoplankton of lakes and reservoirs. They tend to form a dense surface bloom rising to the surface and drift to form massive suspensions which may be 1 m in depth. They are a major health concern because some species produce highly toxic secretions which cause skin irritation and serious stomach upset if consumed. The main genera in lakes and reservoirs are *Microcystis*, *Anabaena*, *Nostoc*, *Aphanizomenon*, and *Rivularia*.

The following is a list of some of the important microorganisms found in water, including lakes and reservoirs.

The following microorganisms are found in water:

Aelosoma A member of the family Aelosomatidae of the oligochaete worms. Found in aquatic habitats.

Amoeba A protozoan of the class Rhizopoda, which moves by the formation of temporary protrusions (pseudopodia).

Arcella A shelled rhizopod protozoan.

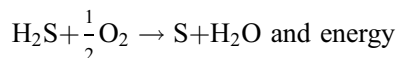
Aspidisca A hypotrichous ciliate found in activated sludge and indicative of good conditions.

Ascaris A parasitic nematode worm of humans (human roundworm), the eggs of which can be disseminated by the way of sewage effluents.

Asellus aquaticus (the water hog louse) An isopod crustacean found in the zone of recovery from organic pollution in a receiving water and therefore a useful indicator organism.

Baetis rhodani A species of mayfly (Ephemeroptera) present in rivers and lakes and tolerant of reduced dissolved oxygen levels in contrast to many other species of mayflies, which are intolerant of such conditions. Consequently, often present under mildly organically polluted conditions.

Beggiatoa A filamentous autotrophic bacterium capable of oxidizing sulfur compounds to elemental sulfur according to the equation:



Bodo A nonpigmented flagellate protozoan usually indicative of unsatisfactory conditions.

Caenis A genus of mayfly which lives on a muddy substratum.

Callitriche An aquatic macrophyte, commonly known as starwort.

Campylobacter First recognized as a source of self-limiting diarrheal disease in the early 1970s and later shown to be the commonest reported cause of acute diarrheal illness (in the UK).

Carchesium A colonial attached peritrichous ciliate.

Chlamydomonas A green flagellate found in nutrient-rich water.

Cladophora A filamentous green alga found commonly in water. It may cause a nuisance by producing excessive growths in nutrient-enriched water or in the final recovery zone in organically polluted receiving water. It is then known as "blanket weed."

Clostridium A genus of spore-forming anaerobic bacteria. *Clostridium perfringens* can form resistant spores which survive in water much longer than other fecal indicators. Its presence implies remote or intermittent fecal pollution. Some species of *Clostridium* can reduce sulfate to sulfide.

Colpidium A ciliate protozoan found in activated sludge.

Cryptosporidium A protozoan parasite found in humans, other mammals, birds, and reptiles. *Cryptosporidium parvum* (*C. parvum*) is a species of *Cryptosporidium* believed to be capable of causing disease in humans and livestock.

Cyclops A copepod crustacean, common in zooplankton.

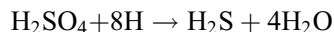
Cysticercosis The bovine effect of infection by *Taenia*.

Cysticercus bovis A parasitic beef tapeworm *Taenia saginata*.

Daphnia A genus of small crustacean of the suborder Cladocera, commonly known as "water fleas." Common member of the zooplankton of lakes and reservoirs and sometimes used as test animals in toxicity tests.

Dendrocoelum lacteum A flatworm (Turbellaria) of the phylum Platyhelminthes. Used as an indicator organism.

Desulfovibrio desulfuricans A bacterium which reduces sulfate to hydrogen sulfide, thus:



Entamoeba histolytica A parasitic ameboid protozoan which causes dysentery in humans and is spread by the contact with polluted water.

Enterobius A nematode worm, parasitic in humans, the eggs of which can be found in polluted estuaries.

Enteromorpha A tubular thaloid green algae related to sea lettuce *Ulva*. Found in brackish and polluted water and especially abundant in polluted estuaries.

Enterovirus A subgroup (genus) of the Picornaviridae family of viruses. Over 70 different types have been isolated from humans. Their normal site of infection is the intestinal tract, but other organs may become involved. Diseases caused range from the trivial to the fatal, including infectious hepatitis, poliomyelitis, and meningitis.

Epistylis A colonial peritrichous ciliate commonly occurring in water treatment works.

Eristalis tenax A dipterous fly with a bee-like appearance, the larva of which (known as the rat-tailed maggot) is aquatic and can, by breathing atmospheric air through a telescopic tail, exist in most organically polluted water and sludge when these are not too deep. Its presence is indicative of organic pollution.

Erpobdella A genus of freshwater leeches, commonly found in streams and lakes, which are useful indicator organisms.

- Escherichia coli* A bacterium living in the alimentary tract of humans and other mammals. As it is passed out with feces in large numbers, its presence in water is indicative of fecal contamination and the possible presence of pathogenic organisms of enteric origin; it is not itself normally pathogenic. Also known as *E. coli*, *Esch. coli*, or *Bact. coli*.
- Fusarium aquaeductum* A common biological-filter fungus having sickle-shaped spores and often having pink coloration.
- Geotrichum* A fungus commonly occurring on biological filters.
- Giardia intestinalis* (*Giardia lamblia*) is a protozoan parasite capable of infecting humans and domestic animals. It causes acute diarrheal illness.
- Glossiphonia* A genus of leeches in freshwater lakes and streams, useful as indicator organisms.
- Gammarus pulex* A freshwater shrimp which may be common in lakes and streams and is a useful indicator organism.
- Helobdella stagnalis* A species of leech, useful as an indicator organism.
- Hydrobaenus* A genus of chironomid midge, an active grazer in some biological filters. Also termed "*Spaniotoma*."
- Hydropsyche* A genus of Trichoptera or caddis flies. In their larval stages, they do not build cases like most caddis but catch their food in nets which they spin in flowing water. Useful indicator organisms.
- Hypogastrura viatica* A species of the primitive insect order Colembola, characterized by having a simple life cycle and by not having wings. A common member of the grazing fauna of many biological filters. Also termed "*Achorutes subviaticus*."
- Legionella* Organisms of the genus *Legionella* are classified as Gram-negative bacteria, of which there are at least 30 species, over half of which have been implicated in human disease. *L. pneumophila* is the causative agent of Legionnaires' disease, an acute pneumonic infection of the lungs, and greater than 85% of cases are caused by *L. pneumophila* serogroup 1.
- Leptomitus lacteus* A nonseptate aquatic fungus found in certain organically enriched water.
- Leptospira icterohemorrhagiae* A pathogenic spirochete which may invade the blood, causing leptospiral jaundice (Weil's disease), transmitted by sewer rats and their urine.
- Leptothrix* A filamentous genus of the iron bacteria. Chlamydoacteriaceae, found in organically polluted water.
- Leuctra* A genus of Plecoptera (stone flies) having aquatic nymphs in flowing water: indicative of well-aerated water.
- Limnaea* A genus of freshwater snail commonly found in fresh water and tolerant of a wide range of conditions.
- Lumbricillus* or *Pachydrilus* A genus of the family Enchytraeidae. Small worms of pale color which are common grazers in biological filters.
- Lumbricus* A genus of worm of the family Lumbricidae which includes the common earthworm.
- Litonotus* or *Lionotus* A genus of free-swimming ciliate protozoa.
- Nitrobacter* A bacterium which converts nitrite to nitrate.
- Nitrosomonas* A bacterium capable of oxidizing ammonia to nitrite.
- Nitzschia palea* A common species of diatom of value as an indicator organism of organic pollution.
- Opercularia* A genus of colonial peritrichous ciliate protozoan common in activated sludge and used as an indicator of its condition.
- Pachydrilus* or *Lumbriculus* Worms of the family Enchytraeidae, commonly found as a grazer in biological filters.
- Paramecium* A genus of free-swimming ciliate protozoa and a useful indicator organism.
- Phormidium* A blue-green algae, the filaments of which intertwine to form a sheet. Commonly found on the surface of biological filters where it may cause ponding.
- Psychoda* A genus of small moth-like flies, the larvae of which are "grazers" in biological filters.
- Potamogeton* Pondweed, which is an aquatic macrophyte with many species growing in ponds and rivers.
- Salmonella* A group of enteropathogenic bacteria responsible for typhoid fevers and food poisoning. Common in polluted water.
- Sphaerotilus* A filamentous bacterium of the order Chlamydoacteriaceae, which may form plumose growths in polluted water known as "sewage fungus."
- Streptococcus fecalis* A bacterial indicator of fecal contamination of water.
- Silvicola fenestralis* A dipterous fly whose larvae are common grazers in biological filters. The adults may cause a nuisance when they leave the filters. Formerly *Anisopus fenestralis*.
- Taenia* A genus of parasitic tapeworm of the class Cestoda, the eggs of which are dispersed through polluted water.
- Tanytus* A genus of chironomid fly, the larvae of which are aquatic.
- Thiobacillus thiooxidans* A sulfur-oxidizing bacterium which, when present in sewage, converts sulfur into sulfuric acid (which, in turn, attacks concrete) according to the equation:
- $$2S + 3O_2 + 2H_2O \xrightarrow[\text{thiooxidans}]{\text{Thiobacillus}} 2H_2SO_4$$
- The bacterium grows best in a strongly acid medium (pH 2.0–6.0) and can also oxidize thiosulfate to sulfate, thus:
- $$Na_2S_2O_3 + 2O_2 + H_2O \xrightarrow[\text{thiooxidans}]{\text{Thiobacillus}} Na_2SO_4 + H_2SO_4$$
- Ulothrix* A filamentous green algae, common in fresh water and on the surface of biological filters.
- Vaucheria* A filamentous green algae, in lakes and streams.

Vorticella A genus of peritrichous ciliate, common in activated sludge.

Zoogloea ramigera A bacterium which grows embedded in a common gelatinous matrix, forming a bacterial slime. A member of the family Pseudomonadaceae.

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Cross-references

[Brownification of Lakes](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Health Aspects of Lakes and Reservoirs](#)
[Lake Restoration](#)
[Light and Primary Production in Lakes](#)
[Nutrient Balance, Light, and Primary Production](#)

MIXING IN LAKES

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Synonyms

Lake water exchange

Definition

Mixing in lakes. The exchange in space and time of lake waters containing different concentrations of matter, promoting the reduction of such differences. A wide range of processes occurs in lakes that induce mixing depending on, for example, wind, waves, heat transfer, and in- and outflows to the lake.

Introduction

Mixing is related to the transport of matter in a fluid (here, the water in a lake), where the matter may be dissolved in the fluid or in particulate form. In the general case, mixing may also occur in connection with the transport of momentum and energy, which for the latter quantity includes heat transport. Mixing implies that the transport reduces or eliminates differences in concentration of the matter in space and time, as fluid elements with different content of matter (concentration) intermingle, causing decreased concentration gradients in the water

body. This decrease in concentration gradients leads to a homogenization of the water body and the evolution toward an equilibrium state, if the forcing conditions are steady.

At the microscale (see Imboden (2004) for a discussion on scales and the motion of lake waters), transport and mixing of matter occur either through advection or diffusion (Fischer et al., 1979). Advection is the transport with the mean flow, whereas diffusion takes place when fluid elements (at the molecular or turbulent scale) are exchanged at no net flow, but with net transfer of matter. At the macroscale, a wide range of processes acts to initiate transport and mixing, for example, heat transfer at the surface or across the lake bottom, in- and outflow to the lake, wind-induced mean currents and waves, and *seiching* (see Imberger and Hamblin, 1982). At the same time, stratification may prevent water exchange since density differences act to dampen turbulence and modify the mean circulation. Most flows in nature are turbulent, although in a lake laminar conditions may prevail leading to mixing primarily at the molecular scale (e.g., ice-covered lakes).

Basic mechanisms for mixing

For turbulent flows, the local velocity at a point in a certain coordinate direction (e.g., x -direction) is typically expressed as $u = \bar{u} + u'$, where $\bar{u}$ is the mean velocity (overbar denotes averaging at a proper time scale) and u' is the turbulent fluctuation (varies in time, but has a zero time-mean value). The local concentration is described in a similar way $c = \bar{c} + c'$, where $\bar{c}$ is the mean concentration (in mass of material per unit water volume) and c' is the turbulent fluctuation. Transport due to advection may be expressed as $m_A = \bar{u} \cdot \bar{c}$, where m_A is the mass transport per unit time and area. This transport refers to a particular coordinate direction, and for the general case a transport vector in three dimensions is obtained. The transport due to diffusion for turbulent flows is obtained as $m_D = \overline{u' \cdot c'}$, where m_D is the mass transport per unit time and area. In computational approaches, m_D is often modeled using Fick's law (Fick, 1855) with the diffusive transport assumed proportional to the concentration gradient according to $m_D = \overline{u' \cdot c'} = -D_x \cdot \partial \bar{c} / \partial x$, where D_x is a turbulent diffusion coefficient. Fick's law was originally formulated for molecular diffusion, which is the prevailing mechanism for mixing under laminar conditions. The coefficient is a material property for molecular diffusion that depends on the matter in the water (e.g., salt, heat), whereas it is a function of the flow for turbulent diffusion. In the latter case the diffusion coefficient may vary substantially in space and time, making it more difficult to determine proper values than for laminar conditions. *Field measurements* are often required to obtain reliable coefficient values.

Changes in the local concentration, which reflects the mixing, occurs because of gradients in the advective and diffusive transport. Such gradients could be present in all

coordinate directions (x , y , and z) leading to the three-dimensional advection-diffusion (AD) equation,

$$\begin{aligned} \frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(\bar{u} \cdot \bar{c}) + \frac{\partial}{\partial y}(\bar{v} \cdot \bar{c}) + \frac{\partial}{\partial z}(\bar{w} \cdot \bar{c}) \\ = \frac{\partial}{\partial x} \left(D_x \cdot \frac{\partial \bar{c}}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \cdot \frac{\partial \bar{c}}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \cdot \frac{\partial \bar{c}}{\partial z} \right) \end{aligned}$$

where t is time and $\bar{u}$, $\bar{v}$, and $\bar{w}$ are the mean velocities in the x -, y -, and z -direction, respectively. The equation above results from a mass balance for a small rectangular element where changes in the in- and outflow over the boundaries cause a change in the mass (concentration) in the element. Changes due to gradients in the advective transport are on the left-hand side and in the diffusive transport on the right-hand side of the equation. In the general case the diffusion coefficient is different in respective coordinate direction, but often in engineering studies, it is regarded as a constant in the area of interest. Solving the AD equation typically involves numerical techniques since the initial, boundary, and forcing conditions are complex for conditions in nature. Also, the mean circulation and turbulence properties have to be obtained from a flow model before the AD equation can be solved.

Mixing processes in lakes

On the macroscale it is possible to identify a number of distinct processes that cause mixing in a lake by inducing circulation and generating turbulence. Simultaneously, density differences due to temperature or salinity often promotes *stratification*, which restricts the flow development and turbulence generation. A stable density gradient counteracts vertical movement induced by the turbulence, thus having a dampening effect on the motion that reduces vertical mixing. Vertical *stratification* often develops in lakes because of low velocity, long residence times, and deeper bottom water (Imboden and Wüest, 1995), which are all factors that tend to reduce mixing. A common type of *stratification* is a two-layer system, where a surface layer (epilimnion) with a lower density develops on top of a bottom layer (hypolimnion) with higher density separated by a relatively thin density interface (i.e., thermocline, if the density difference is due to temperature). Such a system may be found in deep lakes in the temperate region during the summer. Furthermore, density differences may drive horizontal exchange of water and contribute to the mixing (Turner, 1973). The most prominent processes that affect mixing in a lake, to be briefly discussed in the following, are wind-induced mean circulation, wind-generated waves, river in- and outflow, heat transfer at the lake surface and bottom, boundary flows, *seiche*, and *internal wave* motion.

When a wind blows over a lake water surface, the shear stress generated at the air-water interface induces a mean drift in the direction of the wind that may set up a circulation in the lake. The transfer of energy from the wind to the lake surface depends on the air and water

densities, the wind speed, and the roughness conditions of the surface (including the presence of surface waves). As a rule-of-thumb, the wind-induced surface current is on the order of 3–4% of the wind speed at 10 m above the surface. For continuity reasons, in a restricted water body such as a lake, if a surface current develops, it has to be balanced by a return current along the bottom or above the density interface, if a two-layer *stratification* is present. Measured vertical velocity distributions from laboratory experiments in channels show that about 1/3 of the upper part of the water column has a current in the direction of the wind, whereas the lower 2/3 experiences a return flow. Wind-induced mean currents and associated turbulence are often the most prominent processes for mixing at the scale of the lake. A secondary flow induced by the wind is the so-called Langmuir circulation (Langmuir, 1938). This circulation, taking place as counter-rotating vortices, may be visualized as streaks on the water surface parallel to the wind direction where floating objects often gather (Leibovich, 1983). A wind speed in excess of 3 m/s is required for the Langmuir cells to form, and the spacing between the streaks depends on the wind speed in an approximately linear fashion.

The wind does not only cause a mean surface current, but waves occur as well that grow in height and period in the direction of the wind. Since the length over which the waves are generated (i.e., fetch) typically is shorter in a lake than in the sea, the waves are correspondingly smaller. Thus, in a small lake the effects of the waves on the lake might be small and limited to the area near the shore. Also, since the waves are typically generated in shallow water, the frictional losses are larger in a lake compared to the sea, acting to reduce wave growth. The waves are primarily causing three types of flow of importance for the mixing in a lake: (1) oscillatory currents at the bottom, (2) turbulence in connection with wave breaking, and (3) mean currents, primarily in the zone of breaking waves (surf zone). When waves are not breaking, they are often assumed to produce negligible net transport of water, and the motion under the waves is taken to be purely oscillatory (linear wave theory, see Dean and Dalrymple, 1984). However, at the bed the frictional losses associated with the wave motion generates turbulence that may cause mixing, and since the boundary layer is considerably thinner under an oscillatory flow compared to a uniform flow, the shear stresses and turbulence generated are larger under the former type of flow. Resuspension of material deposited on the lake bottom is often initiated by the wave motion at the bed.

Waves break when they become too steep, expressed through the wave height/wavelength ratio, or when the wave height/water depth ratio exceeds some critical value (on the order 1). The breaking is associated with marked turbulence generation that causes strong mixing. Homogenization of the surface layer in a stratified lake is promoted by wave breaking due to excessive steepening, whereas depth-limited breaking in shallow water

mobilizes bed material and initiates strong vertical and horizontal exchange. Wave breaking in shallow water also generates mean currents as the wave momentum flux decreases with the wave height reduction. The mean currents cause frictional forces that balance this decrease in momentum flux. The most pronounced current occurs if the waves break at an angle to the shoreline, creating what is known as a longshore current. A mean cross-shore current also develops (perpendicular to the shoreline), as water transported onshore in the upper part of the water column is returned along the bottom (often denoted undertow). The cross-shore current is typically considerably weaker than the longshore current, and thus of less importance for the transport and mixing. The nonlinearity of the waves, especially in shallow water before breaking, gives rise to a net drift of water in the wave direction that will induce a mean current. This current is often referred to as the Stokes drift. In a limited water body, a return flow develops that balances the Stokes drift.

Water entering or exiting a lake through a river or a similar water course also induces movement and mixing in the lake, although in general at the local scale. The relative importance of such discharges for the mixing can be assessed from the lake residence time, which is the time needed to replace the entire lake water volume by the inflow. The river water is often discharged to the lake in a jet-like manner where strong mixing takes place at the jet boundaries, entraining lake water and mixing it with the river water. This entrainment sets up a circulation in the lake extending to a region that depends on the lake geometry and the river discharge properties. At some distance from the point of discharge, the river water will become completely mixed with the lake water, losing all of its initial characteristics. This distance may extend many initial river widths. Water exiting a lake also initiates a mean flow in the lake. However, this flow typically affects a smaller region as the acceleration of the water toward the exit occurs with less energy dissipation and turbulence. In- or outflow through the ground water and inflow due to precipitation could also be important for lake mixing under certain conditions. If the water entering the lake has a different temperature or salinity, density differences may affect the discharge. Different types of man-made discharges, such as flows from sewage or cooling water outfalls, also contribute to the mixing locally.

Heat transfer at the water surface, and to a lesser degree at the bottom, causes temperature gradients in the lake, with associated differences in density, that induce mean currents. This mechanism for transport and mixing is of great significance, especially in the temperate areas where the annual cycle of lakes is a direct result of the varying heat transfer at the water surface during a year. Whether a lake will receive a net gain or loss of heat depends on the heat balance at the surface, where the most important components are incoming short- and long-wave radiation, reflected short- and long-wave radiation, emitted long-wave radiation from the water, free and forced convection (e.g.,

evaporation/condensation), and conduction. A heating up of the surface water implies a lowering of the water density and the development of a stable *stratification* (deeper water is colder and has larger density) that often leads to two-layer *stratification* in deeper lakes. This situation prevails during the summer. If the surface water is cooled down, the density increases and unstable conditions may develop where the density of the surface water is greater than the density of the underlying water. In this case, a downward flow is initiated with strong mixing as a result on a scale of the entire lake. When a lake is ice-covered, the heat exchange at the surface is negligible and the heat transfer at the bottom could become important for causing density-driven flows and mixing.

Flow over a boundary, such as the lake bottom, gives rise to shear stresses and associated turbulence generation. A more uneven, or rougher, bottom provides more resistance to the flow, enhancing turbulence generation, which may locally, close to the boundary, induce mixing. Thus, in a lake with highly variable bottom topography, local mixing near the bottom can be significant. Furthermore, if the bottom features are sufficiently large, zones of separation will develop downstream the feature with additional turbulence generation and recirculation. In such recirculation zones, local areas may arise where the mixing is smaller and material is deposited. A hole or trench in the lake bottom often causes the accumulation of fine material with possible local problems for the water quality.

Water blowing over the lake surface not only generates a mean current, but water is also pushed in the wind direction causing a tilt in the water surface over the lake, known as wind setup, with the maximum rise at the most downwind point. The size of the wind setup is primarily a function of the wind speed, the lake water depth, and the length over which the wind is blowing. In some lakes, if the wind ceases to blow after building up a marked setup, the water surface gradient induces a strong return flow that may create a setup at the opposite lake side, overshooting the mean water level. This in turn produces a flow back toward the other lake side, and an oscillatory behavior occurs that is known as a *seiche*. The *seiching* causes a mean circulation that transports and mixes the lake water. If the lake is stratified, a tilt in the water surface will produce a corresponding displacement in the density interface that is significantly larger since it is inversely proportional to the density difference between the surface and the bottom layer. The circulation in the surface layer will also induce water movement in the bottom layer through the shear generated along the density interface, but this movement is small and typically negligible.

Under certain conditions, disturbances from the surface layer can initiate waves in the density interface similar to the waves generated by the wind on the lake surface. These waves, known as internal waves, propagate along the interface, causing water movement, but typically not implying prominent mixing. However, if the internal waves become too steep, they may break and under such circumstances mixing becomes strong.

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Cross-references

Basin-Scale Internal Waves
 Double-Diffusive Convection in Lakes
 Hydrodynamics and Circulation of Fjords
 Ice Covered Lakes
 Initial Mixing of Pollutants
 Internal Seiches
 Stratification in Lakes
 Thermal Regime of Lakes

MYPONGA RESERVOIR, SOUTH AUSTRALIA: THE INFLUENCE OF NUTRIENTS, PHYTOPLANKTON, PATHOGENS, AND ORGANIC CARBON ON WATER QUALITY

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Definition

This essay describes the water quality related impacts of nutrients, organic carbon, pathogen, and phytoplankton dynamics, in an intensively studied source water reservoir used for the production of potable water.

Water quality

Water quality in reservoirs supplying water treatment plants is determined by the interaction of the physical, chemical, and biological processes that occur in the

catchment and within the reservoir. Storage of water within reservoirs provides security in terms of water quantity, but also gives the opportunity for both beneficial and undesirable changes in water quality to occur. Good reservoir management can optimize the beneficial changes and mitigate risks to water quality. There is often distinct seasonality in streamflow and transient events, such as rain event inflows, that are important for many reservoirs that supply water for potable consumption. Threats to water quality may be esthetic in nature, or may pose a serious risk to human health. Contamination of reservoirs may result from the growth of toxic cyanobacteria or the transport of pathogenic organisms from the catchment (see below). These threats to water quality may be generated over different time scales. Threats associated with rain events may occur at hourly to daily timescales, whereas changes to phytoplankton communities may take longer to manifest. Another risk factor is contamination by anthropogenic toxins (pesticides, endocrine disruptors, petroleum); these factors are either accidental and essentially stochastic, or chronic system properties that are not considered here. Other threats to water quality may be both chronic and transient. The concentration of natural organic matter in a reservoir fluctuates relatively slowly, but during periods of high streamflow, changes in its concentration and character may occur, and warrant management of the reservoir offtake. Here we demonstrate, using Myponga Reservoir as a case study, the importance of rainfall patterns and hydrodynamics for the determination of raw water quality for potable water production.

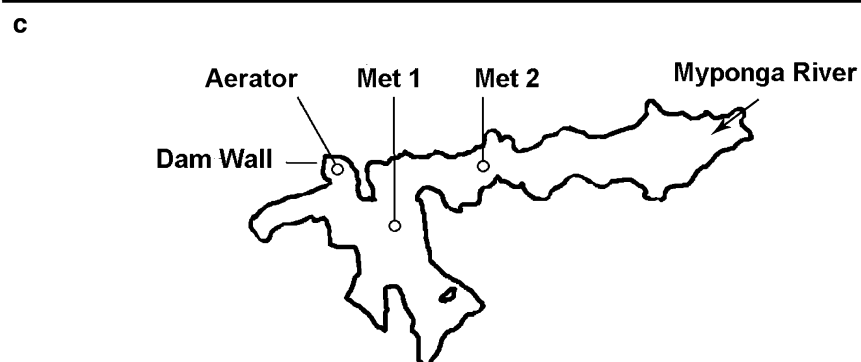
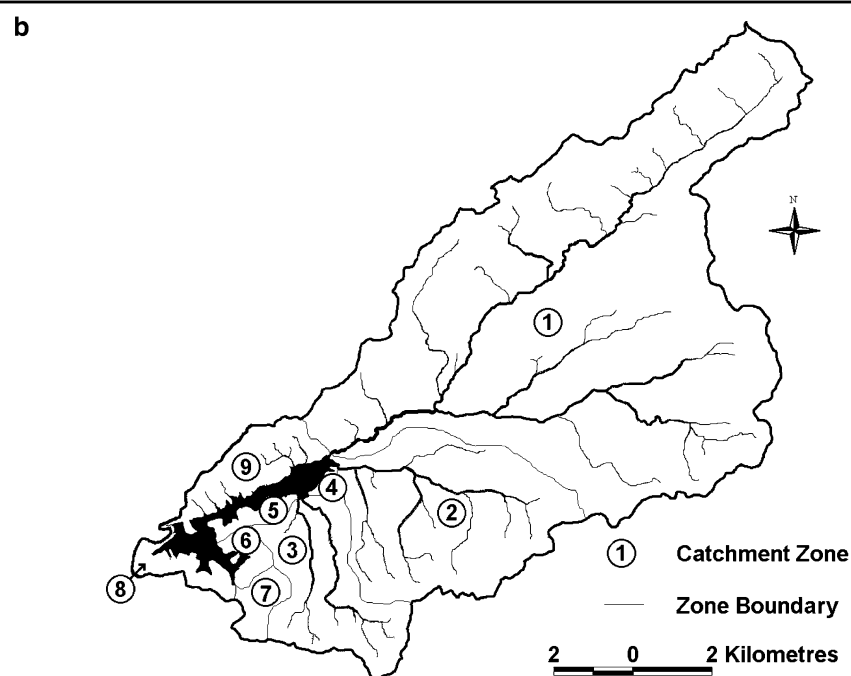
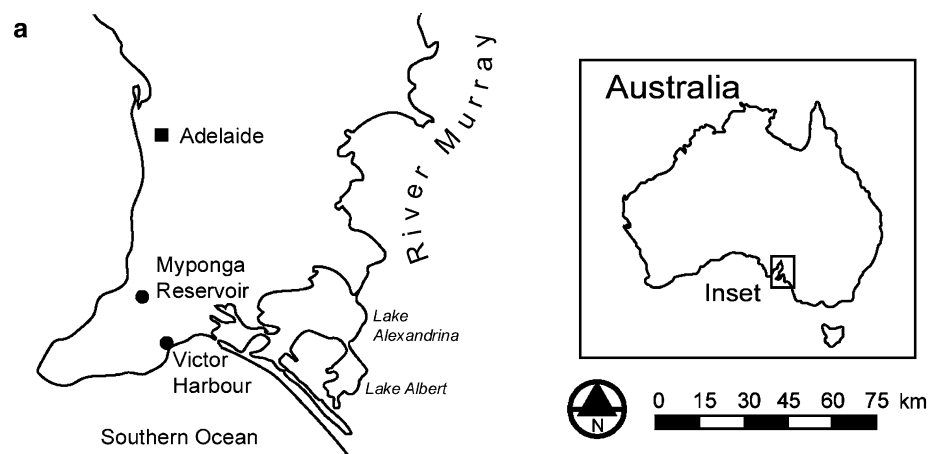
Myponga reservoir

Description/characteristics

Myponga Reservoir (S 35° 21' 14", E 138° 25' 49"), situated 70 km south of Adelaide, South Australia (Figure 1a), is a drinking water supply reservoir with a maximum depth of 42 m and a volume of 26,800 mL at full supply level. It has a catchment of approximately 124 km² of mixed land use, including improved pasture for dairy, beef and hay production, plantations of *Pinus radiata*, and patchy remnant native vegetation. A survey of dominant land use estimated 62% livestock grazing and 24% dairying (Thomas et al., 1999). The reservoir is artificially destratified, which reduces the release of contaminants from sediments (Brookes et al., 2000), and hence the nutrient load to the water column is dominated by catchment sources. Summer chlorophyll maxima range from 10 to 50 mg m⁻³, while annually, water temperatures range from 10°C to 25°C. The dissolved organic carbon concentration is 10–12 mg L⁻¹ with high color (55–65 HU) and generally low turbidity (<5 NTU). The water treatment plant is a dissolved air flocculation flotation type (DAFF) supplying similar to 10 ML day⁻¹ in the winter months and similar to 50 ML day⁻¹ in the summer months.

Nutrient load

The annual load from the catchment of nitrogen and phosphorus varies significantly with the streamflow



Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 1 (a) Location of the reservoir in South Australia, Australia. (b) The catchment of Myponga reservoir showing the sub-catchments and water courses. Myponga river is the main water course in catchment zone 1. (c) Schematic of Myponga reservoir showing the locations of the dam wall, aerator, meteorological stations (Met1, Met2), and the inflow of Myponga River.

regime, determined by the interannual variability in rainfall (Linden et al., 2004). Calculating the mass balance of nutrients between the inflows and the offtakes revealed that Myponga Reservoir retained 80–90% of the inflowing phosphorus in two consecutive years with similar rainfall, yet different streamflow (Table 1). In 1999, there were fewer rainfall events that generated high streamflows and subsequently reduced the transport of nutrients from the catchment. In 2000, almost 40% of the annual catchment load of phosphorus was delivered during flows above 200 ML day⁻¹. This work identified that remedial works for reduction of catchment loads, such as wetlands or ponding basins, must function at flow rates greater than 25 ML day⁻¹, as this is the flow regime when the majority of phosphorus is delivered to Myponga Reservoir (Table 2). The annual loads of nutrients themselves do not present a threat to water quality, but the consequences for the growth of phytoplankton are important from a water quality perspective.

Phytoplankton

Concentration

The absolute concentration of algal cells in the reservoir raw water is relevant for the water treatment as algal-derived organic carbon can be precursors for disinfection by-products (Graham et al., 1998) and contribute substrates for the formation of biofilms in distribution systems. The relationship between phosphorus loading and maximum chlorophyll concentration in lakes and reservoirs is well known (Dillon and Rigler, 1974; Harris,

1994; Vollenweider, 1975). Chlorophyll responded in a predictable manner to phosphorus concentrations in Myponga Reservoir (Figure 2), and this was largely driven by external inputs. Some years were considered to be outliers, where the linear relationship between phosphorus concentration and peak chlorophyll did not hold. In 1988, the dry spring meant that the supply of phosphorus and the phytoplankton growing season were asynchronous. The strong stratification observed in 1993 resulted in a larger than normal internal load that decoupled the relationship between Chl *a* and total phosphorus. Since 1994, additional commitment of resources to artificial destratification has probably prevented this from occurring again (Brookes et al., 2000).

Composition

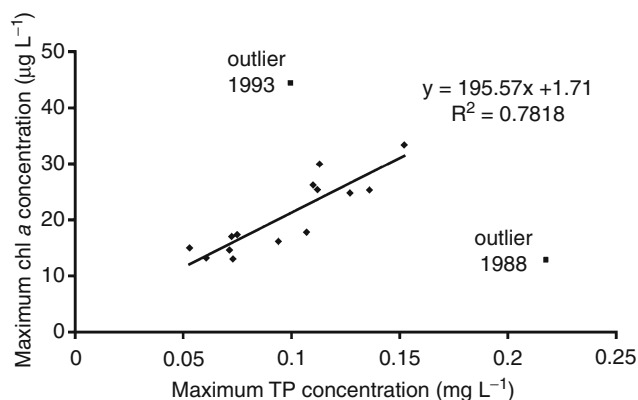
The composition of the phytoplankton community has great bearing on water quality. The presence of cyanobacteria (blue-green algae) is a concern as they can produce compounds that taint the taste and odor of water and several species produce toxins (Steffensen et al., 1999). Many cyanobacterial species produce gas vesicles which are hollow gas-filled structures in cells which provide buoyancy and reduce sedimentation losses. The gas vesicles confer an advantage during periods of water column stability (Walsby, 1994) when denser species tend to sink. *Anabaena circinalis* seasonally compromises the esthetic raw water quality in Myponga Reservoir by producing geosmin particularly during periods of shallow vertical mixing when its numbers rapidly increase (Lewis

Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Table 1 Annual catchment load and rainfall characteristics for Myponga reservoir in 2 years where the nutrient load from the catchment was studied. See Figure 1b for sub-catchment boundaries (Modified from Linden et al., 2004)

Year	Rainfall (mm)	Gauged flow from sub-catchment 1 (ML)	Annual load in kg (percent retained)				
			Total phosphorus (TP)	Filterable reactive phosphorus (FRP)	Ammonium (NH ₄)	Oxidized nitrogen (NO _x)	Total Kjeldahl nitrogen (TKN)
1999	788	5,196	2,518 (82)	1,283 (86)	546 (65)	1,351 (47)	11,516 (32)
2000	750	10,780	5,485 (89)	2,307 (87)	1,100 (78)	1,192 (23)	28,662 (76)

Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Table 2 Total phosphorus load and flow classification in 1999 and 2000 (Modified from Linden et al., 2004)

	Year	Daily flow (<5 ML)	Daily flow (5–15 ML)	Daily flow (15–25 ML)	Daily flow (25–50 ML)	Daily flow (50–100 ML)	Daily flow (100–200 ML)	Daily flow (200–500 ML)
Load (kg)	1999	24.0	118	57.3	119	118	221	117
	2000	22.4	77.9	87.5	224	203	410	663
% of annual total load	1999	3.1	15.2	7.4	15.4	15.2	28.5	15.1
	2000	1.3	4.6	5.2	13.3	12.0	24.3	39.3
Flow (ML)	1999	257	1,180	580	785	765	1,160	465
	2000	186	842	804	1,250	1,290	2,270	4,157
% of annual total flow	1999	5.0	22.7	11.2	15.1	14.7	22.4	9.0
	2000	1.7	7.8	7.5	11.5	11.9	21.0	38.5



Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 2 Regression between observations of annual maximum total phosphorus (TP) concentration and the annual maximum chlorophyll a concentration in Myponga reservoir. The outlier years of 1988 and 1993 are not included in the regression and are discussed in the text.

et al., 2004). Artificial destratification, with bubble plume aeration and mechanical mixing, has been applied at Myponga Reservoir, with the combined goals of reducing cyanobacterial growth and controlling iron and manganese release from the sediments by preventing hypoxia. Artificial destratification does not always prevent or reduce the growth of problematic cyanobacteria (Antenucci et al., 2005b), but the principle of its influence on community dynamics by changing the vertical mixing regime is sound and it is often effective (Heo and Kim, 2004; Visser et al., 1996). The composition of the phytoplankton community at Myponga Reservoir was investigated with a monitoring program, a series of ecophysiological investigations of photosynthetic and growth responses, and modeling studies.

Important taxa found in the phytoplankton community at Myponga include cyanobacteria (e.g., *Anabaena*, *Microcystis*, *Phormidium*, *Planktothrix*, *Aphanocapsa*, *Oscillatoria*), Chlorophytes (e.g., *Ankistrodesmus*, *Chlamydomonas*, *Chlorella*, *Oocystis*, and *Scenedesmus*), Diatoms (e.g., *Cyclotella* and *Nitzschia*), Chrysophytes (e.g., *Chroomonas*, *Cryptomonas*), and dinoflagellates (e.g., *Peridinium*). It is generally dominated by green algae and diatoms, which rely on turbulence to remain entrained; the conditions when cyanobacteria grow to significant biovolumes is restricted to short periods each year (Figure 3) when there is a shallowing of the surface mixed layer and high nocturnal air temperatures that inhibit lake cooling. Ordination between the phytoplankton community dynamics and physical and chemical conditions revealed that the dominant processes determining the composition of the phytoplankton community were the surface mixed layer depth and the concentration of inorganic nitrogen and filterable reactive phosphorus. Due to stable periods with shallow mixing in the summer

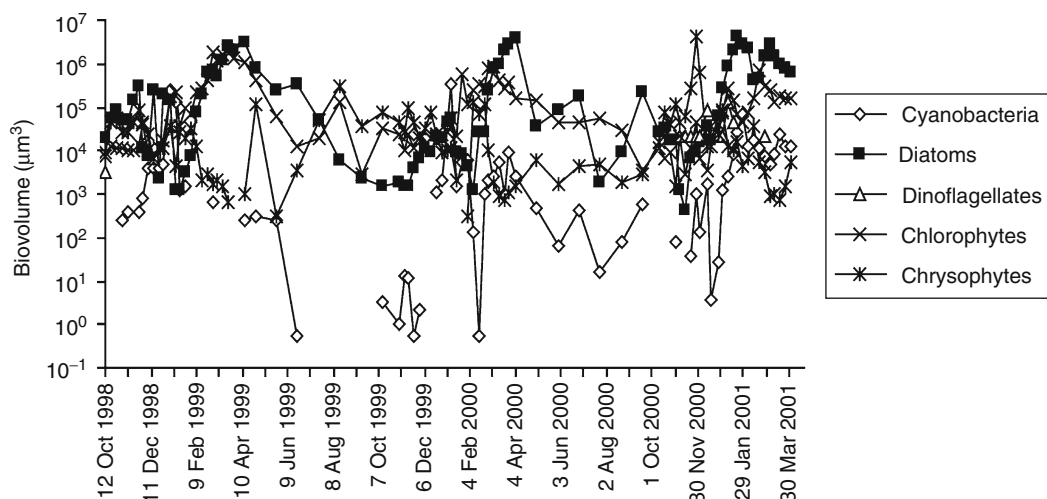
periods, the destratification system was unable to mix sufficiently deeply to restrict *Anabaena* growth by light limitation. Experimental investigation of *Anabaena* grown in bottles at different depths and, therefore, light doses, suggested that, at euphotic to mixed layer depths ratios (Z_{eu}/Z_{mix}) above 0.2, this species would grow rapidly at summer irradiances.

Modeling the growth of *A. circinalis*

To expand on the empirical understanding of the occurrence of cyanobacteria within the reservoir, the growth of these problematic organisms can be modeled, providing a useful management tool (Lewis et al., 2004). Application of a physical-biological coupled model, such as DYRESM-CAEDYM, allows the testing of destratification scenarios to evaluate their effectiveness to attenuate the growth of cyanobacteria. Lewis et al. (2004) found that the destratification systems employed at Myponga Reservoir reduce the peak *A. circinalis* biomass to approximately a third of their potential peak biomass in the absence of mixing. Despite this, the use of algicides remained a reservoir management strategy for these periods. Alternatives, such as advanced treatment processes, such as ozonation and activated carbon may be considered to deal with episodes of geosmin in source waters. However, the contribution of artificial destratification to the control of this threat to water quality was demonstrated. Recently, the bubble plume aerator has been switched off during periods of very high cyanobacterial abundance. This allows the cells to float upward where they tend to form “blooms” at the surface and subsequently lyse. This protects the deep offtakes from high concentrations of cyanobacteria and prevents them from entering the treatment plant. Residual geosmin in the source water is removed with powdered activated carbon dosed at the intake to the water treatment plant.

Pathogens

The pathogens that threaten water quality originate from catchments, generally as the result of contamination by microbes (*E. coli*, *Clostridium*, etc.) or protozoa (*Cryptosporidium* spp., *Giardia* spp.) from livestock or sewage systems. Consequently, rain event inflows present a significant challenge to water quality as they carry these hazards into the reservoir. Pathogens can be inactivated by sedimentation, exposure to UV light, grazing, and natural mortality (Brookes et al., 2004). These processes are influenced by the length of time the pathogens spend in the reservoir and by their distribution. This, in turn, is determined by the processes of dispersion, dilution, horizontal and vertical transport. Of particular importance is the hydrodynamics of pathogen-containing inflows. The behavior of inflows is controlled by their density relative to that of the lake water, such that warm inflows will flow over the surface of the lake as a buoyant surface flow and cold, dense inflows will sink beneath the lake water where they will flow along the submerged reservoir basin

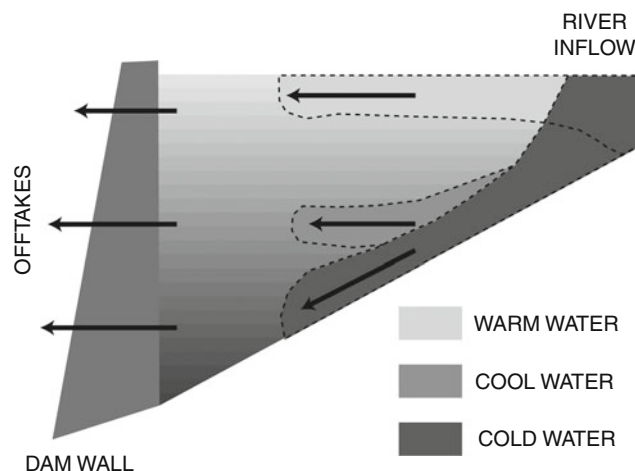


Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 3 Sum of biovolumes measured for the different taxonomic groups observed at Myponga reservoir.

channel toward the deepest point. In either case, the inflow will entrain water from the lake, increasing its volume, changing its density, and diluting the concentration of pathogens and other characteristics. In the case of a dense underflow, when its density matches that of the adjacent lake, the underflow will become an intrusion. In some cases, the underflow is denser than any water in the lake, and it will flow all the way to the deepest point (Figure 4). This is of particular interest, as in the majority of drinking water reservoirs the deepest point is often where the offtake to drinking water supply is located (i.e., at the dam wall). Given that oocysts will survive longest in cold and dark water, this underflow mechanism can potentially produce the greatest risk. Using knowledge of the properties and behavior of riverine intrusions allows the extraction of water from outside of this zone and will minimize the pathogen risk.

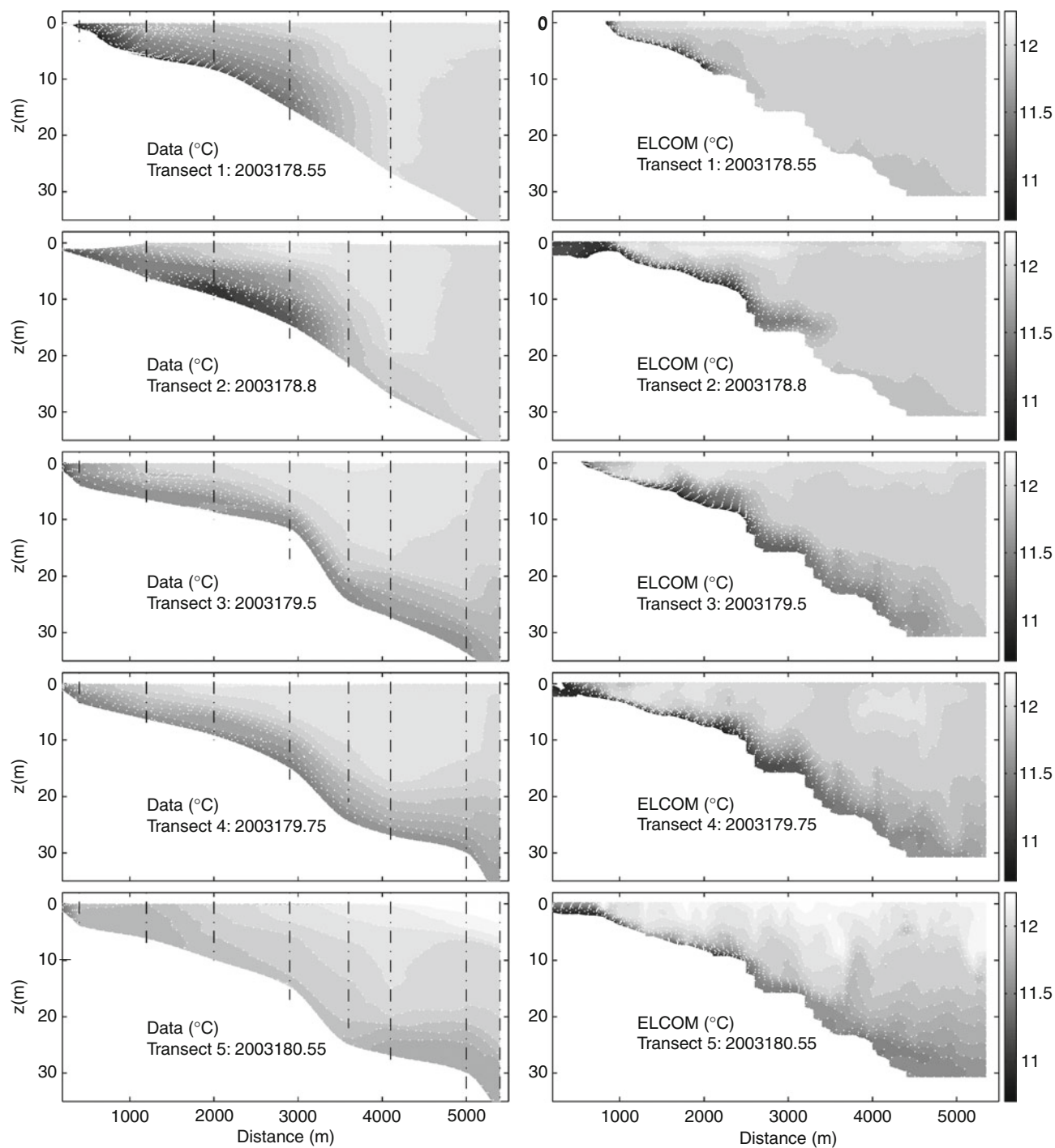
Inflow hydrodynamics

A comprehensive case study of the movement of pathogens from the catchment to the reservoir offtake was undertaken at Myponga Reservoir. The reservoir had two meteorological stations installed to measure wind and solar radiation and thermistor chains that were used to assess the hydrodynamic conditions within the water body (Figure 1c). Flow and temperature were also measured in the inflow of the main river at the v-notch gauging weir. An intense sampling program followed a large rainfall event (58.4 mm) and a hydrodynamic modeling study was performed (Figure 5). Despite the mean retention time based upon abstraction rates being approximately 3 years, the riverine intrusion reached the dam wall within 36 h (Brookes et al., 2005). Targeted sampling of the intrusion revealed the heavy pathogen load carried by the intrusion (Brookes et al., 2005; Hipsey et al., 2006). This

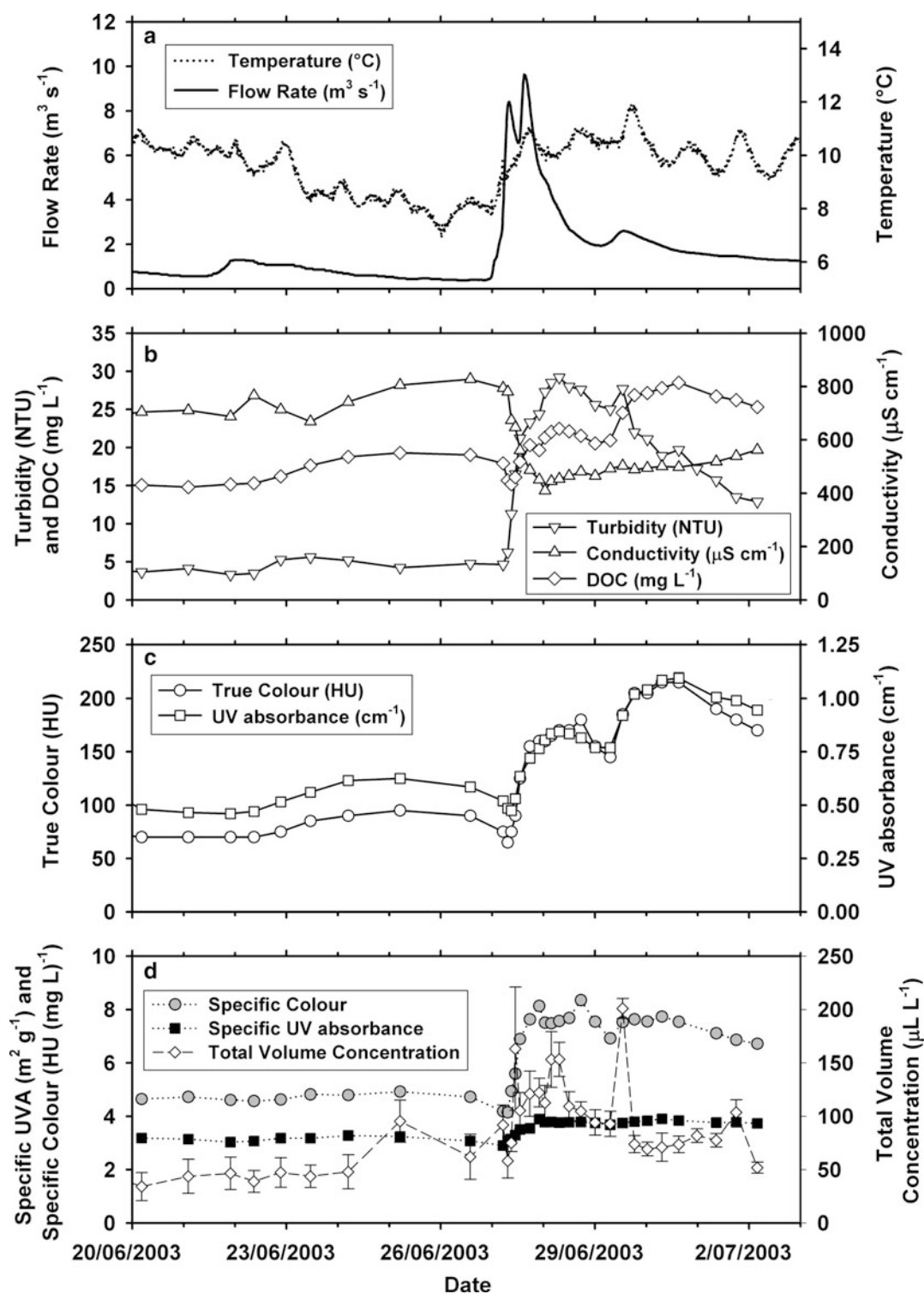


Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 4 Formation of intrusions during inflow events. The density of the water is represented by the shading. The coldest and most dense water is shaded the darkest. Reservoir density stratification has been represented as an arbitrary linear gradient. The depth of formation of the riverine intrusion will correspond to the depth in the reservoir of equivalent density.

experiment allowed the reexamination and revision of existing pathogen monitoring regimes by demonstrating the correlation, or indeed the lack thereof, between the hydrodynamic distribution of surrogates of fecal contamination and the pathogen oocysts (Brookes et al., 2004, 2005; Hipsey et al., 2006). The invaluable data provided by the experiment assisted in the development and validation of models of transport and dilution of microbial



Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 5 Temperature data collected during the inflow event showing riverine intrusion penetrating the reservoir to the dam wall and simulation results from ELCOM (From Hipsey et al. (2004)). Transect 1: 2003178.55 is 1312 h June 27 2003, Transect 2 is 1912 h June 27 2003, Transect 3 is 1200 h June 28 2003, Transect 4 is 1800 h June 28 2003, Transect 5 is 1312 h June 29 2003. Vertical dot dash lines indicate locations of temperature profiling.



Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 6 Water quality and quantity at the Myponga river v-notch weir monitored using a flow triggered auto-sampler. Samples were collected every 50 mL of flow. (a) Flow rate ($\text{m}^3 \text{s}^{-1}$) and water temperature ($^{\circ}\text{C}$). (b) Dissolved organic carbon (mg L^{-1}), turbidity (NTU), and conductivity ($\mu\text{S cm}^{-1}$). (c) True color (HU) and UV absorbance (cm^{-1}). (d) Specific UV absorbance and specific color and average total volume concentration of particles ($\mu\text{L L}^{-1} \pm \text{SD}$ determined within each single sample with a LISST-100, Sequoia Instruments, USA).

pathogens during riverine transport (Antenucci et al., 2005a; Hipsey et al., 2004, 2008). The fecal coliforms were associated with particles (Hipsey et al., 2006), while the *Cryptosporidium* oocysts were free floating (Hipsey et al., 2004), and the differences in settling behavior means that using surrogates alone could result in underestimation of protozoan pathogen dilution and therefore overestimation of risk reduction (Brookes et al., 2005). The combination of knowledge of reservoir dilution dynamics is therefore important for calculating the effectiveness of the reservoir as a barrier to pathogen intrusion into the water treatment system. Complex three-dimensional hydrodynamic models provide the best understanding of individual events but may be impractical for informing management responses in real time without considerable investment. Simpler dilution models that capture the key processes are available and are a potential management tool (Antenucci et al., 2005a).

Natural organic matter

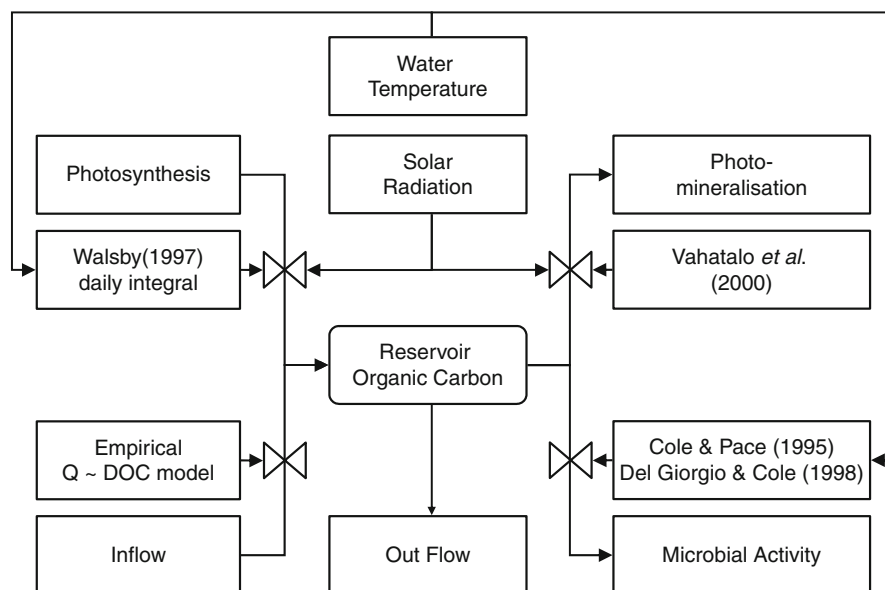
Natural organic matter (NOM), the complex polymerized residuals of decaying biomass (predominantly vegetation), imparts color to waters and is a precursor for disinfection by-product formation. In waters of low turbidity, it is a major target for removal by the water treatment process and that which is not removed contributes to the growth of biofilms in the distribution system and increases chlorine demand. Being chemically indistinct, it is useful to apply characterization methods to NOM, which describe its properties according to size (HPSEC; Chow et al., 2009), functionality (resin fractionation; van Leeuwen et al., 2002), and suitability as a microbial substrate (microbial regrowth potential; Page et al., 2002). The quantity and character of organic matter found in a drinking reservoir is the product of the sources of organic matter and the processes acting upon it. Aspects of organic matter dynamics including catchment loads, hydrodynamic transport, and microbial degradation were investigated in the Myponga Reservoir system (catchment and reservoir) with a flow weighted monitoring program in the main sub-catchment, an intensive investigation of the same flow event, as described in the section on “Pathogens” above, and modeling studies (Linden, 2007).

The sources of NOM in reservoirs are allochthonous (derived from outside the reservoir; i.e., the catchment) and autochthonous (produced within the reservoir; i.e., by phytoplankton and aquatic macrophyte growth). River discharge often has a significant influence on the organic carbon concentration in flowing water (Schlesinger and Melack, 1981), and therefore the delivery of allochthonous NOM. This influence has been attributed to the flushing and mobilization of old soil water (Pearce, 1990; Pearce et al., 1986). Often a hysteresis is observed with organic carbon concentrations being greater on the rising hydrograph than on the falling hydrograph (Grieve, 1984; Moore and Jackson, 1989). However, the opposite is generally observed at Myponga Reservoir (see Figure 6

for an example). In total, nine peak flow events were analyzed for concentration-flow (*C-Q*) hysteresis by the methods of Butturini et al. (2006). These observations suggested that there was generally a temporal separation in the surface and ground water contributions to flow occurring in the Myponga River catchment and that significant hysteresis occurred. Seven of the nine events analyzed had anticlockwise hysteresis rotations implying increased DOC concentrations on the falling hydrograph. Such information is vital to inform management responses; the greatest increases in NOM concentration in the inflowing river water may be found on the falling hydrograph and follow the threat caused by pathogens carried by the flow front by many hours (Linden, 2007).

The flow event shown in Figure 6 was the same event as was intensively sampled as described in the section on “Pathogens” above. Samples were also collected for determination of NOM properties to assess the changes in raw water quality. Empirical modeling of recommended coagulant doses (van Leeuwen et al., 2005) predicted only small increases in the coagulant dose requirements for the observed changes in raw water quality on the basis of NOM and turbidity changes (7.2% increased cost in treatment chemicals); 40% of this increased coagulant dose was attributable to changes in the NOM. There was a relatively small impact of raw water quality in this event; however, investigations in other systems have demonstrated greater impacts of inflows on NOM character and its amenability to removal by water treatment (Hobson et al., 2010). Reservoirs seem to generally provide a significant barrier or buffer for changes in raw water quality from the perspective of NOM as generated by riverine inflows.

The longer term perspective of the benefits of water storage reservoirs should also be considered as they retain significant quantities of organic matter. The annual allochthonous organic carbon load at Myponga Reservoir was estimated to be 240 ± 110 t (mean 1999–2003 $\pm$ SD) on average, four times greater than the estimated autochthonous carbon load of 60 ± 34 t (Linden, 2007). However, in a year of very low rainfall (2002), the estimated autochthonous and allochthonous loads were similar. Therefore, in terms of mass, the catchment delivers a significantly greater amount of organic carbon than the water storage process generates. The mass of organic carbon taken into the WTP was similar to 100 t/year, while the loss of a similar amount could be attributed to consumption by the microbial community, as estimated by applying existing models (Cole and Pace, 1995; del Giorgio and Cole, 1998). The application of models of photomineralization (Vahatalo et al., 2000) implied the loss to this process was an order of magnitude less than microbial metabolism (see Figure 7 for budget structure; Linden, 2007). In short, reservoirs provide significant ecosystem services for the provision of better raw water quality over short and long timescales from the perspective of natural organic matter.



Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality, Figure 7 Diagram of calculation of organic carbon mass balance for Myponga reservoir. Arrows indicate flow of carbon or information to model formulations.

Conclusions

Understanding the processes that determine raw water quality at the outlet of the reservoir is a multidisciplinary challenge. Options for the management of reservoir water quality are available in both the catchment and the reservoir; however, critical control points are generally limited to the reservoir offtake. A holistic view of the role of reservoirs in water quality can improve water quality by providing the water treatment plant with the best raw water quality possible, for a given system, and give it the best chance of providing the best quality water to the customer tap.

Acknowledgments

The South Australian Water Corporation that managed the water supply during the time of the research conducted must be duly acknowledged for its commitment to water quality research, in conjunction with the Cooperative Research Centre for Water Quality and Treatment. The criticism of management practices at the reservoir must be considered as criticism of the water industries' best available management options. Further, the authors' views consist of focussed examination of particular events and periods of time, which they consider representative, but cannot always consider all aspects of reservoir management, such as economic and legal constraints. The authors would like to thank all their colleagues who have worked with them including David Lewis, Rod Boothey, Allan Brown, Rudi Regel, John Van Leeuwen, Rolando Fabris, Peter Hobson, Jason Antenucci, Dennis Steffensen, and Don Bursill.

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Cross-references

[Carbon Cycle in Lakes](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Light and Primary Production in Lakes](#)
[Nutrient Balance, Light, and Primary Production](#)
[Reservoir Sedimentation in Australia under Extreme Conditions](#)

N

NAHUEL HUAPÍ, LAKE

Rhodes W. Fairbridge (Deceased)

Definition

Nahuel Huapi is a glacial lake in the Patagonian Andes, near the boundary with Chile, at 765 m (2,516 ft) elevation. It is located in Neuquén Province on the edge of Rio Negro Province. Its area is 549 km² (212 mi²). It is 65 km (40 mi) long, 8 km (5–6 mi) wide, and up to 300 m (1,000 ft) in depth. It has several fjord-like arms. An area of 7,848 km² (3,030 mi²) is protected as a national park. In the SW is Mt. Tronador (over 3,350 m), which is covered by glaciers. Its scenery is spectacular, and the area is now a tourist destination, the town of San Carlos de Bariloche being situated on the SE shore. It is drained by the Limey R., which discharges into the Rio Negro.

Cross-references

[South America, Lakes Review](#)

NASSER LAKE

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Site

Lake Nasser lies between latitudes 23°58'N and 20°27'N and longitudes 30°07'E and 33°15'E (Kim and Sultan, 2002; Ball, 1927; Dasco 1998a, b). The total length of the reservoir is about 500 km, with 150 km in Sudan (Lake Nubia) and 350 km within the Egypt's borders (Kim and Sultan, 2002; Ball, 1927; Dasco, 1998a), see Figure 1.

The lake has a surface area of 600 km² and an average width of 12 km (Dasco, 1998b). The total storage capacity

of the lake is 160 × 109 m³, of which nearly 20% is considered dead storage (i.e., water is not released from this part of the lake regardless of the downstream needs). This zone receives and retains sediments during flooding.

The lake is home to an impressive variety of birds, mammals, and reptiles. More than 100 species of birds live on its shores, including wild duck, Egyptian geese, pelicans, herons, egrets, and various species of hawks, kites, and falcons. Monitor lizards, Dorcas gazelle, jackals, desert fox, and other smaller desert mammals can also be observed.

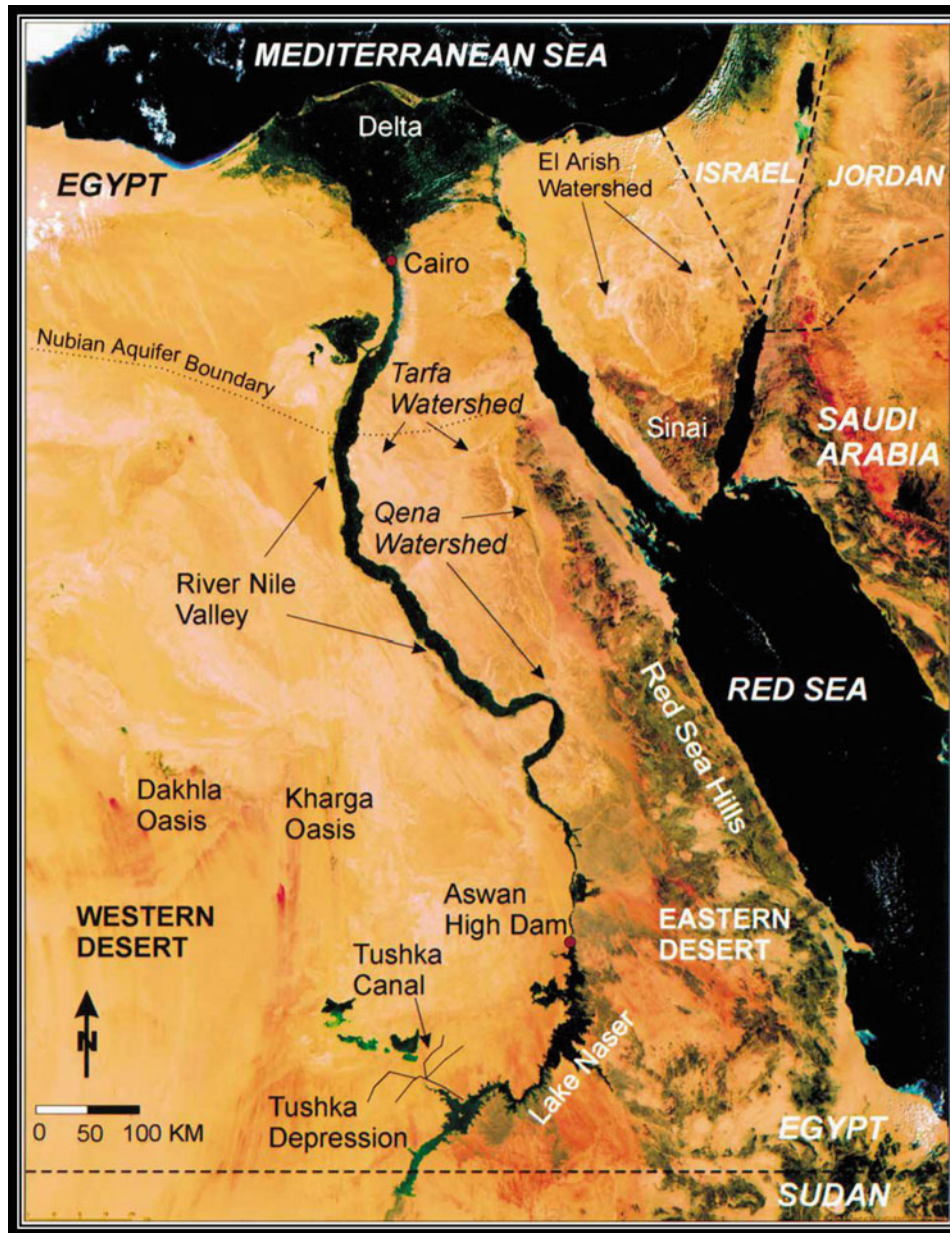
Lake Nasser has, arguably, the best freshwater fishing in the world for both Nile perch and tigerfish. There are also several subspecies of catfish and two kinds of tilapia. In all, there are around 32 species of fish in the lake. The two main fishing techniques used are trolling and shore fishing. Shore fishing requires more skill than trolling and usually yields more fish. Although trolling is more popular, larger fish can be caught shore fishing, the record catch being 179 lbs.

Because the Lake Nasser reservoir is approaching its maximum storage capacity, the depressions west of Lake Nasser in the southwestern Desert of Egypt (Figure 1) are used as a natural flood diversion basin to reduce possible downstream damage to the Nile Valley caused by exceptional flooding (Kim and Sultan, 2002).

The major strategic units and the ground water table level in Lake Nasser are shown in the hydrogeologic map (Figure 2a) and the schematic cross section (Figure 2b) along line A-A.

Climate change assessment

Changes in water level interact with the physical features of Lake Nasser to yield both positive and negative geoenvironmental impacts (El Gammal, 2010; Nile Research Institute (NRI), 2006; El-Sersawy and Farid, 2005). Two strangle portions in the course of the lake are examined. One is the El Madiq strangle zone, where sands fall and drift on the stream gradient to the narrow course



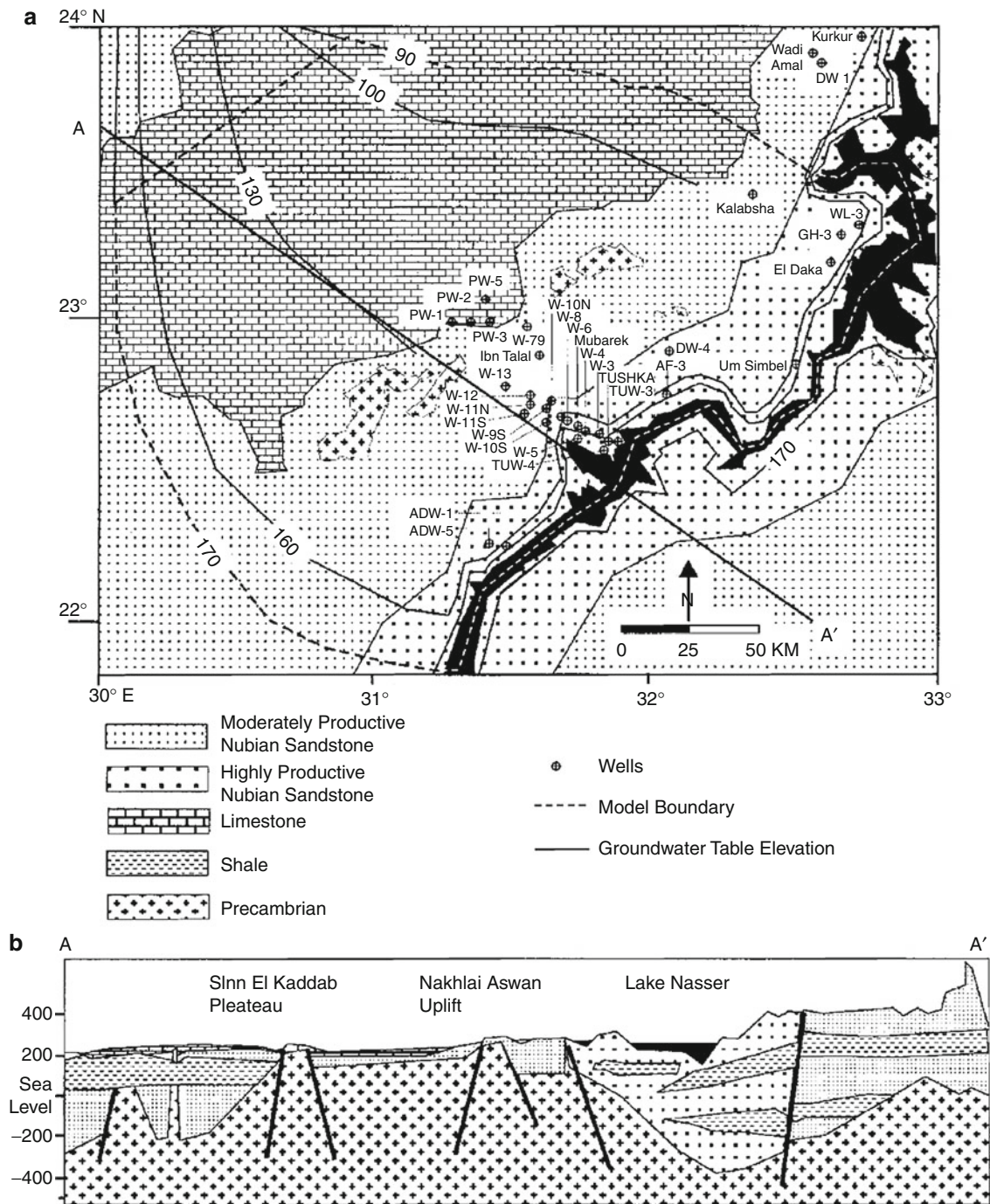
Nasser Lake, Figure 1 Moderate resolution imaging spectroradiometer satellite image acquired February 19, 2000 (Kim and Sultan, 2002).

that appears as shallow water on satellite imagery. The other is the entrance of the lake, a site of new delta initiation, with maximum thickness concentrated in a zone lying between 350 km and 420 km of the dam. Two positive impacts have been found: in Allaqui, the difference in water area between 1987 and 2000 was 91.9 km², and the difference in water extension was 25.54 km.

In Allaqui, fine soil in an area about 30,121 km² in the basin can be cultivated. The saturated water zone in Kurkur is close to the land surface and subject to

transpiration and evapotranspiration. Kurkur vadose water can flow to the lake course and interflow water can migrate back to the land surface to evaporate. An area of 392 km² available for agriculture protects the Kurkur area from evaporation (El Gammal, 2010).

To detect changes in the water level in Lake Nasser a remote sensing technique was used with Landsat TM images from 1972, 1987, 2000, 2003, and 2008 using the ArcMap program and Geographic Information System (GIS) (Figure 3).



Nasser Lake, Figure 2 Simplified hydrogeologic map of the study area (Kim and Sultan, 2002). (a) Major hydrogeologic units, model boundaries, and locations of pumping and piezometric wells. (b) Northwest-southwest, trending schematic cross section, along line A-A in panel (a).

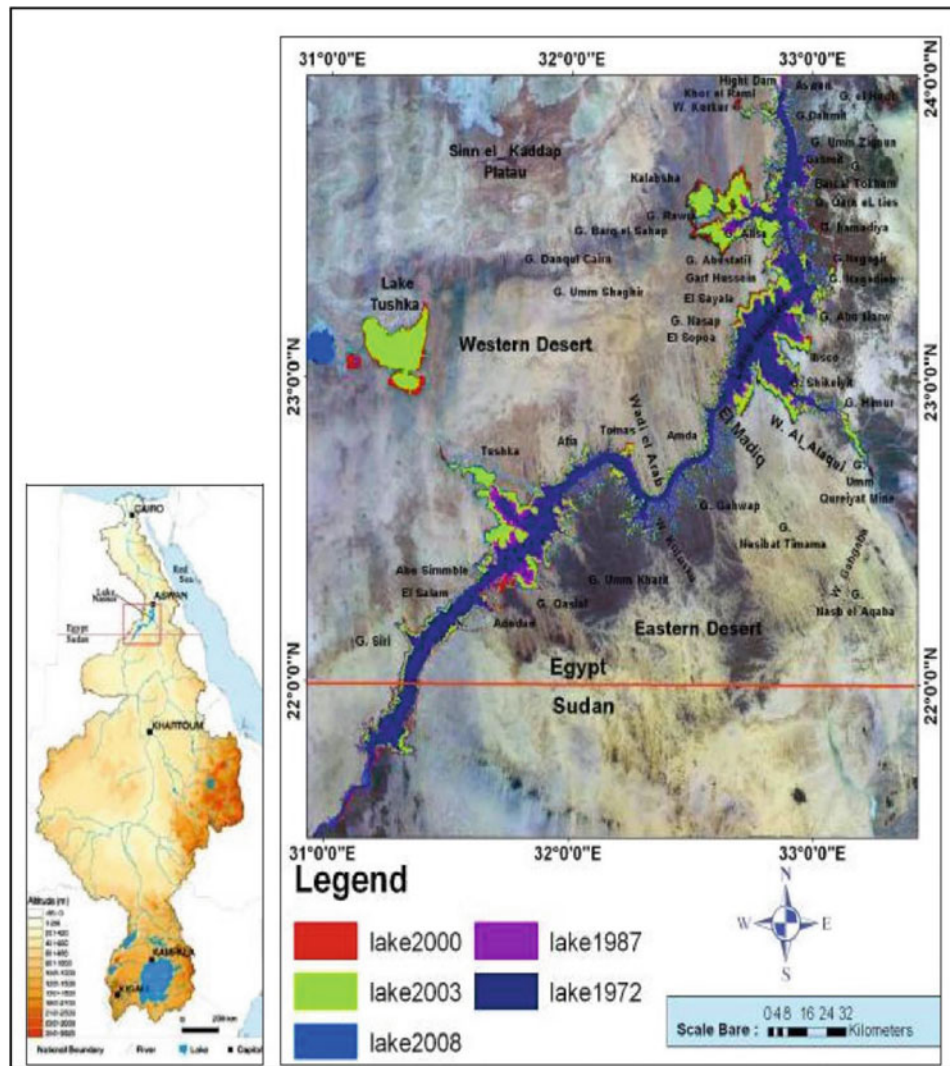
Strangle problems

El Madiq strangle (Gorge) zone

In the course of River Nile, the shallow water gorge portion stretches from El Madiq to Kurusku, 27.6 km in length and 2.7 km average width (including the El Madiq

strangle portion, which is 1.1 km width and 4.6 km in length) (Figures 3 and 4).

Before the high dam, the water velocity increases in speed, with more erosion in flanks, and passes toward the north. After the dam, the water velocity decreases



Nasser Lake, Figure 3 Change detection on Lake Nasser in multi-temporal dates (El Gammal, 2010).

and sand deposition has increased due to change in global climate. Water goes through narrow, incised wadis (khors) in the eastern bank with altitude 150 m in troughs (Figure 4). These khors are traced in hard Nubian sandstone, which is already saturated with water and is considered an underground water reservoir before the dam construction.

Sediment concentration

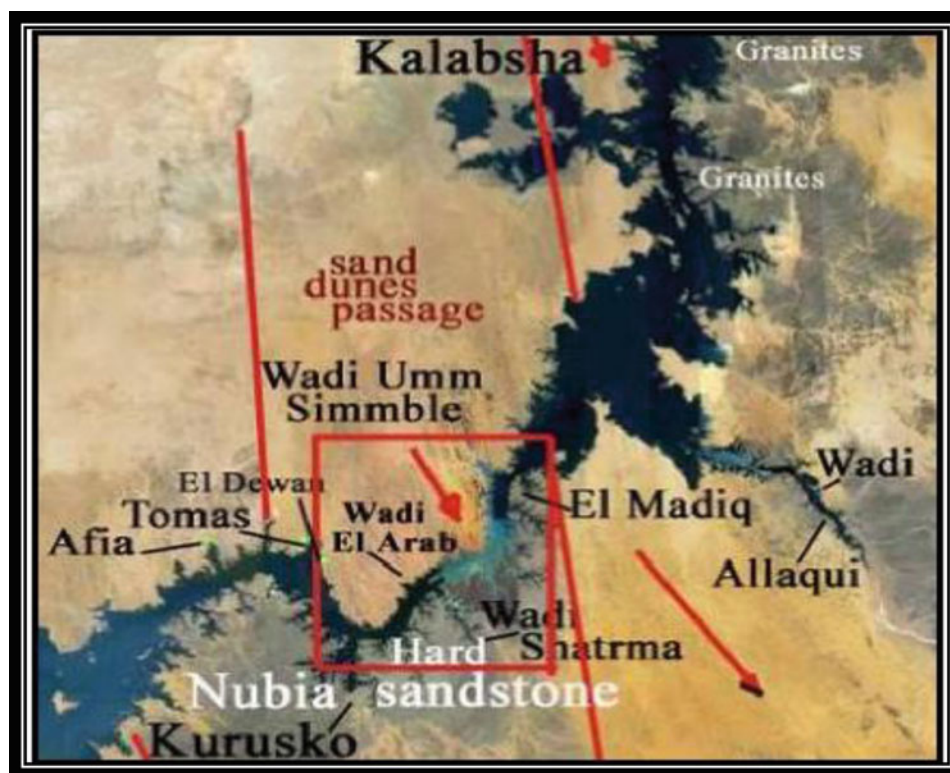
Before construction of the High Dam in 1964, about 93% of the total average annual suspended load of 124 million tons/year was carried out to the Mediterranean Sea. After the High Dam construction, flood discharge of the Nile downstream has been greatly modified and more than 98% of the total suspended load was retained within the reservoir and the total amount of sediment transported

downstream of the dam dropped to only 2.5 million tons/year due to a decrease in water velocity.

In 2000, the average water velocity was 0.52 m/s at 487 km south of the High Dam and in 2001, it was decreased from 0.46 m/s at the entrance of the lake to 0.04 m/s.

The deposited material within the Egyptian border was equal to 56 Mm³(million cubic meters) between February 2007 and March 2008 and the total sedimentation volume through March 2008 was 1123 Mm³. In Sudan, the sedimentation between February 2007 and March 2008 equaled 200 Mm³ and the total sedimentation volume through March 2008 was 5161 Mm³ (Nile Research Institute reports 2000 and 2006).

At Halfa in 2006, the total volume of sedimentation was 1.673 Bm³ (billion cubic meters) at water levels less than



Nasser Lake, Figure 4 El Madiq shallow zone and sand encouragement on Lake Nasser from the Western Desert (El Gammal, 2010) (Note: The arrows indicate wind direction and sand movement).

147 m, and 3.345 Bm³ between water levels 147 m and 175 m; there was no sedimentation above water level 175 m. Consequently, the water can spillway to the north at 170 m. The total volume of sedimentation in the lake was 6,284 Mm³ from 1964 to 2008 (18% in Egypt and 83% in Sudan), while in cross section 26 (the second cataract at 357 km from the High Dam, Figure 5) it was 1,037.44 Mm³ during the same period in Halfa, forming a new delta from 1968 to 2008 in a zone including the following localities;

- Gemi (372 km from the dam), sedimentation thickness = 59.82 m
- Qengari 6 (394 km from the dam), sedimentation thickness = 57.89 m
- Murshed 3 (378.5 km from the dam), sedimentation thickness = 54.49 m
- Old Second Cataract, sediment thickness = 52.10 m

An estimated annual average of 160 million tons of sediment reached El-Gaafra Gauging Station (34 km to the north of the High Dam downstream) during the period from 1904 to 1963; the annual sediment load varied from 50 million tons to 228 million tons per year (Nile Research Institute (NRI), 2006).

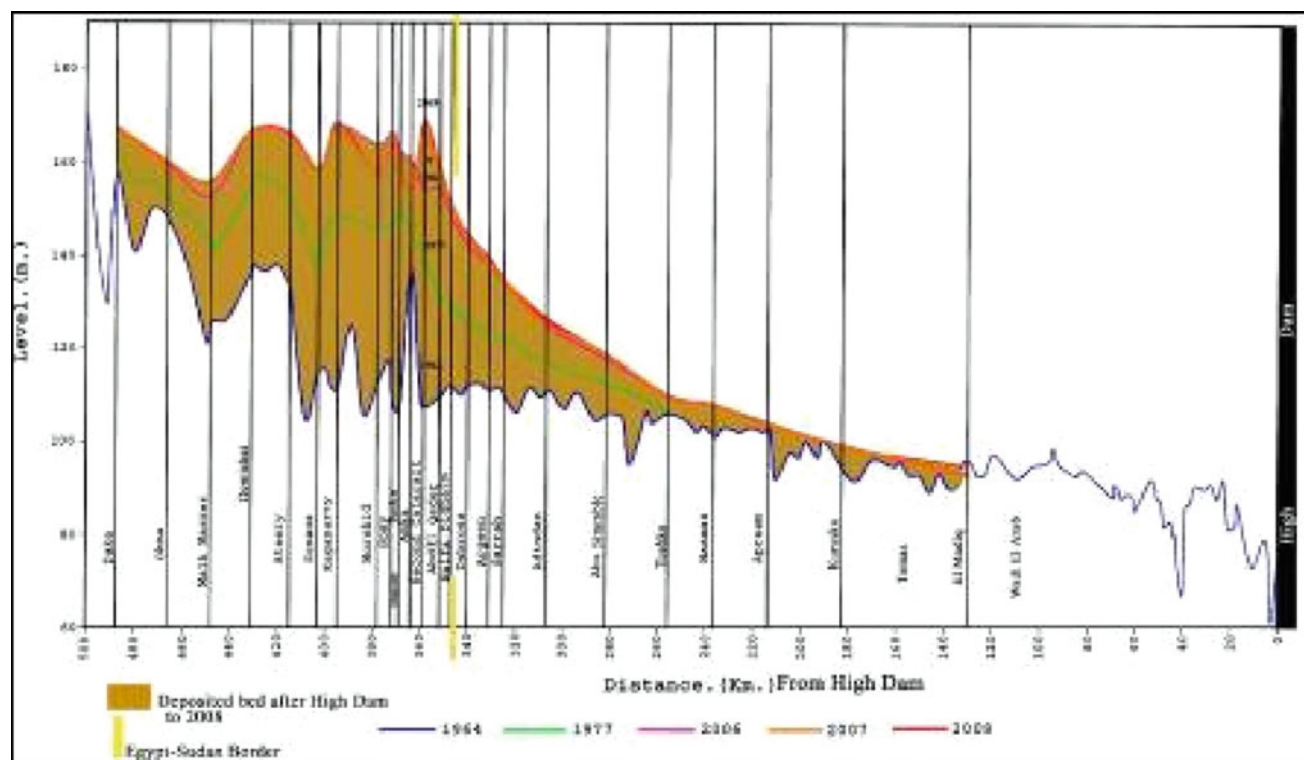
The suspended sediment concentration peaks at El-Gaafra have dropped from 3,000 ppm before lake

initiation to only 50 ppm after the construction of the lake (El-Sersawy and Farid, 2005).

Evaporation estimates

An update of evaporation estimates, using local meteorological and hydrological data collected from instrumented platforms (floating weather stations (FS)) at three locations on the lake, Raft, Allaqi, and Abusembel (respectively, at 2, 75, and 280 km upstream of the Aswan High Dam), is given in Figure 6 (Elsawwaf et al., 2010).

Results from six conventional evaporation quantification methods were compared with the values obtained by the Bowen ratio energy budget (BREB) method. The results of the BREB method showed that there is no significant difference between the evaporation rates at Allaqi and Abusembel. At Raft, higher evaporation rates were obtained, which were assumed to be overestimated due to the high uncertainty of the Bowen ratio (BR) parameter. The average BR value at Allaqi and Abusembel was used to eliminate this overestimated evaporation. Variance-based sensitivity and uncertainty analyses on the BREB results were conducted based on quasi- Monte Carlo sequences (Latin hypercube sampling). The standard deviation of the total uncertainty on the BREB evaporation rate was found to be 0.62 mm day⁻¹.



Nasser Lake, Figure 5 Illustration of the deposited bed inside Lake Nasser, prepared from data collection of the mentioned references.

The parameter controlling the change in stored energy, followed by the BR parameter, was found to be the most sensitive. Several of the six conventional methods showed substantial bias when compared with the BREB method. These were modified to eliminate the bias. When compared with the BREB-based values, the Penman method showed most favorably for the daily time scale, whereas for the monthly scale, the Priestley-Taylor and the deBruin-Keijman methods showed best agreement. Differences in mean evaporation estimates of these methods (against the BREB method) were found to be in the range 0.14 and 0.36 mm day⁻¹. All estimates were based calculations at the daily time scale covering a 10-year period (1995–2004) (Figures 7 and 8).

Impact of summer thermal stratification on depth profile of phytoplankton productivity, biomass, density, and photosynthetic capacity

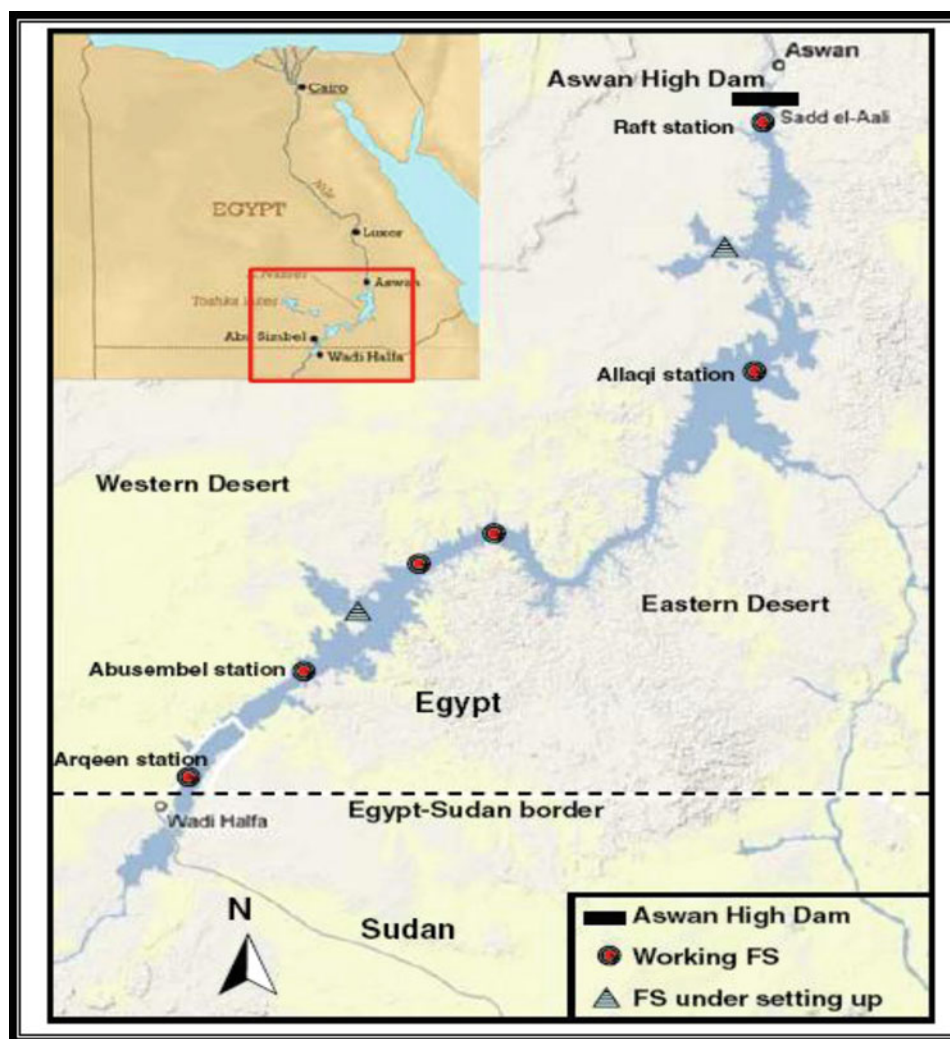
In winter, there is a complete upwelling in the water body; in the summer, it is clearly thermally stratified (Abd El-Monem, 1995, 2008; Abdel and Goma, 1993; Entz and Latif, 1974; Reynolds, 1984; Chang and Bradford, 1985; Tilzer, 1983; Carpenter et al., 1987; Grobbelaar and Stegmann, 1976; Robarts, 1984; Haberl, 2007). Depth profile of summer stratification at the upper 15 m was investigated at four different sites. Temperature

amplitude reached about 10°C, whereas oxygen concentration was about 7.491 mg O₂ l⁻¹.

The epilimnion layer was extended to 10 m depth, whereas the metalimnion went from about 10–15 m, and the hypolimnion was below that. Bands of stratification were affected with the inflow of the River Nile at the south. Peak maximum of chlorophyll a, phaeophytin, and standing crop was recorded at 10 m. Net primary productivity was irregular along the depth profile. Superficial water had climax photosynthetic capacity and declined downward. Integrated column productivity was correlated with that equivalent concentration of chlorophyll a. Khore Korosko exhibited the highest integrated productivity rate (315.9 mg C m⁻² h⁻¹) and photosynthetic capacity (24.4 mg C mg Chl⁻¹ h⁻¹) among the studied sites.

Layering width of water stratification and its temporal occurrence were affected by current and physics of flooded water. Thus, the epilimnion is usually shallow in the north and becomes deeper toward the inflow of Nile floodwater at the south.

To represent water body and depth profile in the main channel and khors during summer thermocline (during July 2005), samples were collected from the upper 15 m depth (the approximate mean depth of the photic zone) at different depths: 0, 3, 5, 10, and 15 m from four sites. One represented the main channel and was located in



Nasser Lake, Figure 6 Map of the Lake Nasser area showing the floating stations (FS) sites and the major physical features of Lake Nasser (Elsawwaf et al., 2010).

El-Madiq. The other three represented the khors (Kalabsha, Korosko, and Tushka) and were located in the deepest position. The sampling sites are shown in Figure 9.

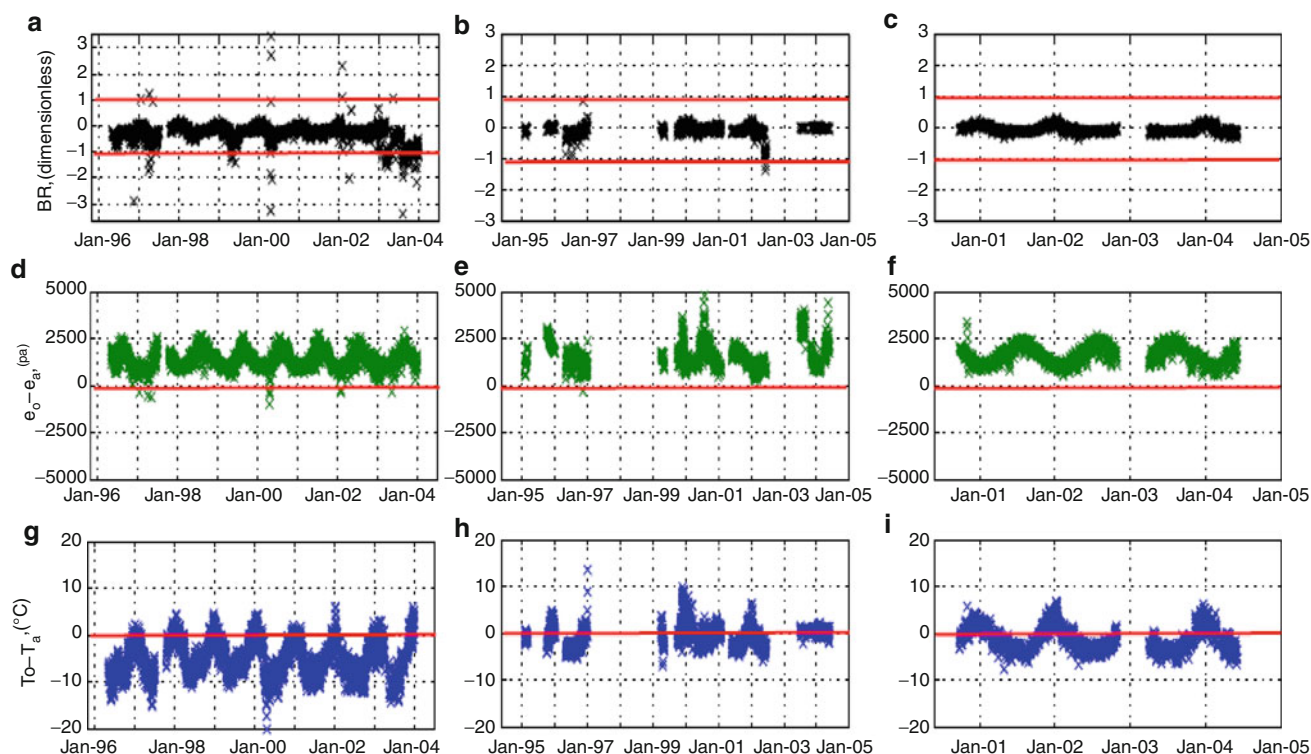
Results were expressed at the given depths per unit volume (m^3) and were integrated to calculate it per unit area (m^2) for that layer. The main morphometric variables of the selected locations are illustrated in Table 1, as reported in Bishai et al. (2000).

Temperature and dissolved oxygen amplitudes, and integrated values of some biological variables for water columns at the study sites in Lake Nasser during summer stratification are indicated in Table 2.

Figure 10 shows water visibility (c) at the studied sites in Lake Nasser, and Figures 11, 12, 13, 14, 15, 16 and 17 indicate depth profile of water temperature ($^{\circ}\text{C}$), dissolved

oxygen ($\text{mg O}_2 \text{ l}^{-1}$), chlorophyll a (mg Chl a m^{-3}), phaeophytin (mg m^{-3}), net primary productivity ($\text{mg C m}^{-3} \text{ h}^{-1}$), assimilation rate ($\text{mg C mg Chl}^{-1} \text{ h}^{-1}$), phytoplankton density ($\text{unit m}^{-3} \times 10^6$), respectively, during summer stratification.

In this study, water visibility in khors was mainly biologically controlled because it was inversely associated with integrated phytoplankton density in that water column ($r = 0.75$). It increased downstream, with a maximum of 3.15 m in Kalabsha. In comparison with the previous investigations, (Abd El-Monem, 1995) found that water turbidity at the northern region of the main channel (downstream) is biologically controlled, whereas on the southern side it was affected with the suspended inorganic matters carried with the flooded water.



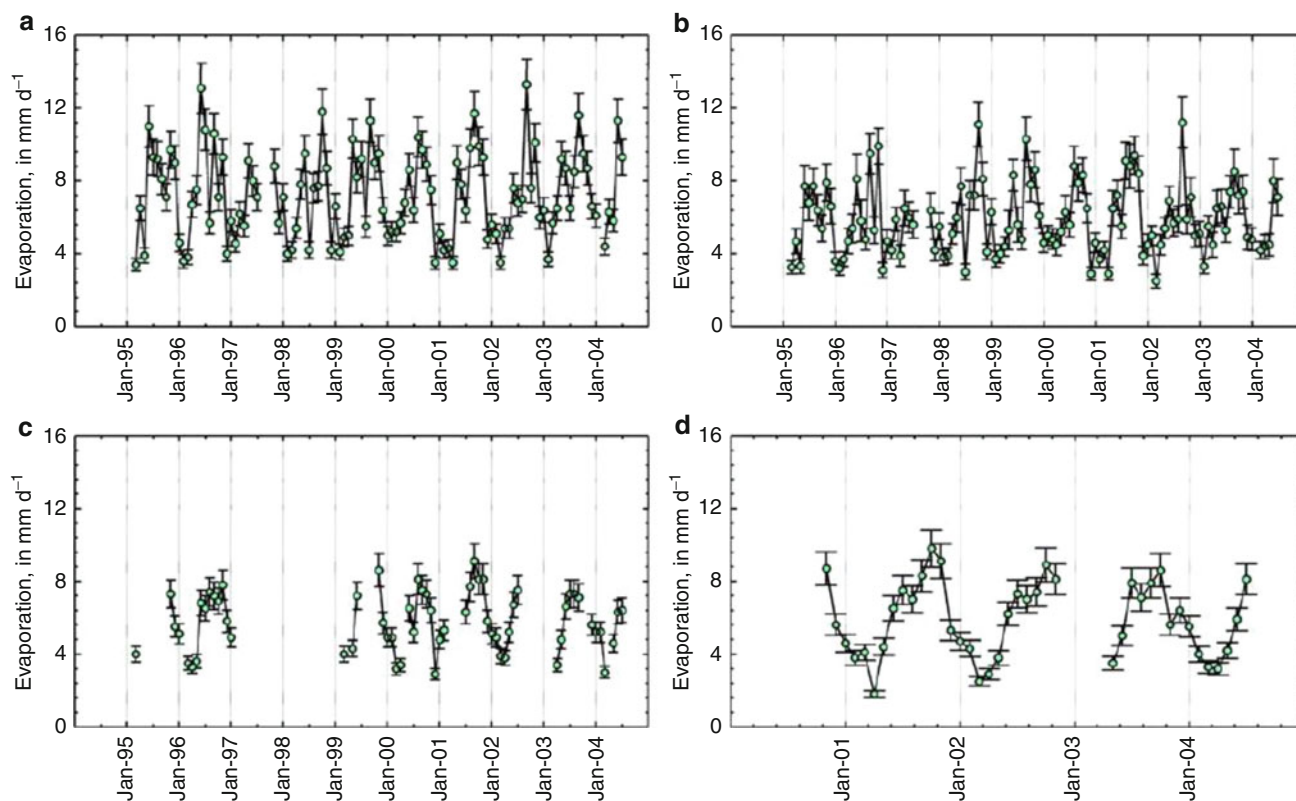
Nasser Lake, Figure 7 Analysis of measurements at three locations on the lake (Raft, Allaqi, and Abusembel). (a–c) Daily average BR value for the period 1995–2004 at Raft and Allaqi stations and for the period 2000–2004 at Abusembel station. (d–f) Vapor pressure difference between the lake surface and 2 m above the lake surface at Raft, Allaqi, and Abusembel stations for the same periods. (g–i) Daily average temperature difference between the lake surface and 2 m above the lake surface at Raft, Allaqi, and Abusembel stations for the same periods.

In winter, there is a complete upwelling in the water body, and the lake lies under unstratified conditions. During summer, however, the water column was thermoclined and the temperature of the water body increased upstream. In the upper layer, water temperature rose to 31.8°C. Difference in water temperature (amplitude) in the 15 m layer varied from 1.4°C in Kalabsha to 5.3°C in Toshka. Its amplitude was increased upstream, but it could extend farther down to 15 m (the studied zone) in the northern khors. This agrees with (Abdel and Goma, 1993).

On this concept, those who surveyed the lake during the filling phase (1972–1973) (Entz and Latif, 1974) reported that the time of total circulation ends in March or April when the stratification starts to develop. The depth of metalimnion is usually initiated at 12–17 m depth, with a peculiar decline to the south. Thus, the epilimnion is usually shallow in the north section and becomes deeper towards the inflow of Nile River water at the south. Under stratified conditions, temperature of the epilimnion rises to 25–29°C. Higher temperatures are unusual, except on very calm days when, within the upper 1–1.5 m, the temperature can rise to 30°C. This may be caused by the decrease of thermal stability of the lake towards the south and the inflowing flood water. Stratification is usually

dissolved from the south, starting in September and completed gradually towards Aswan in November.

Spatial distribution of dissolved oxygen (DO) along the water column showed that oxygen distribution has a similar trend as that of the temperature. Thus, water depth up to 10 m was well oxygenated and represented the epilimnion layer, while metalimnion can be extended to 15 m depth, and hypolimnion layers below that. The value of hypolimnion was the widest near the High Dam; and diminishes to the south. Concerning yearly cycling of DO, (Entz and Latif, 1974) found that water is saturated to the bottom during winter circulation. From March, when the enormous development of the phytoplankton starts, there is a strong increase in DO content within the surface layer up to 14–18 mg O₂ l⁻¹. However, because of the increased thermal stability, the metalimnion is formed and the hypolimnion becomes increasingly poorer in oxygen. The gradient of DO in the metalimnion layer, which occurs when the hypolimnion becomes severely deoxygenated, creates a chemically diverse layer. The main loss of oxygen in that layer is probably due to decomposing sinking plankton organisms forming the so-called plankton rain. The bacterial activity might be the most vivid just below the metalimnion.



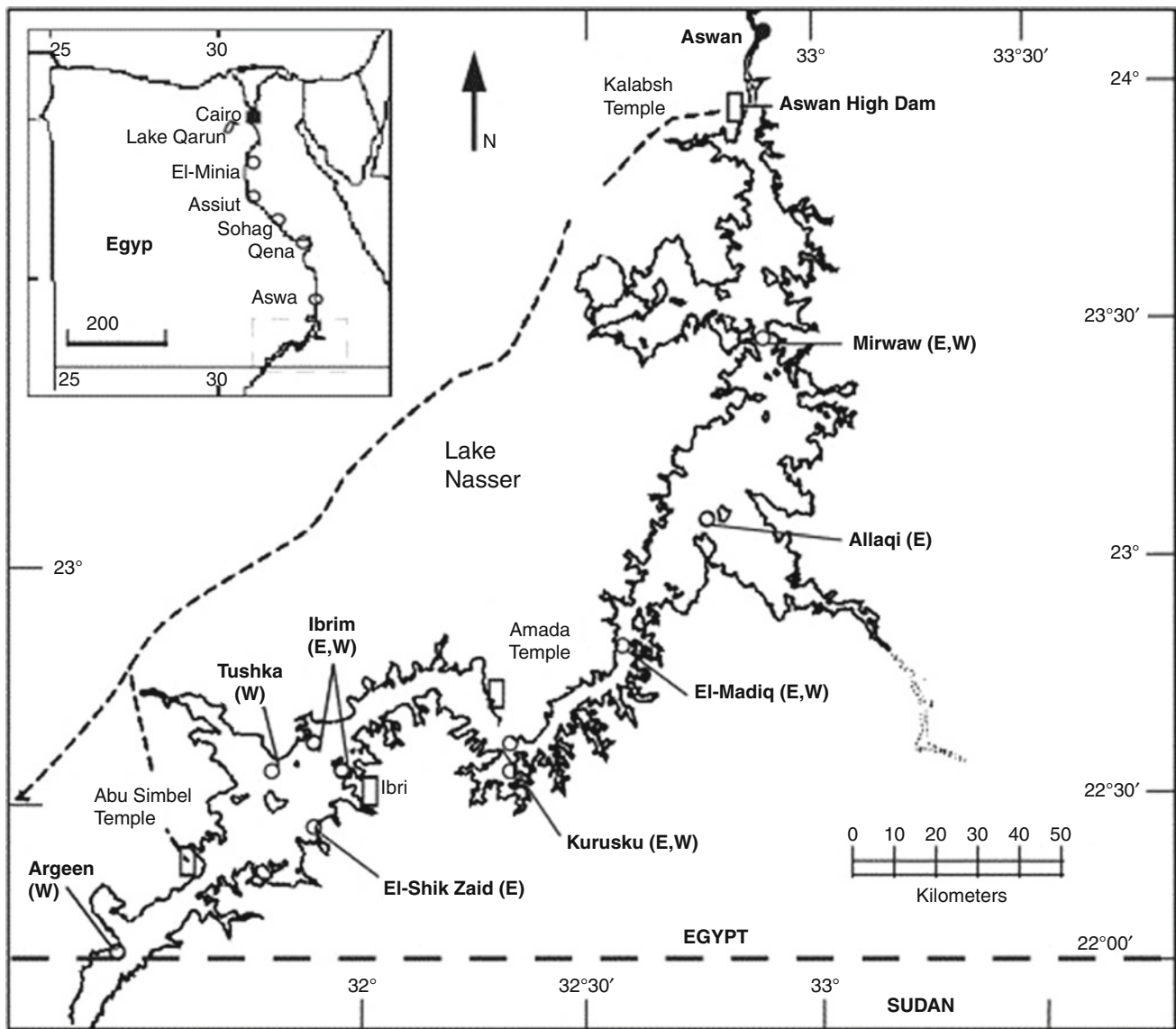
Nasser Lake, Figure 8 Daily evaporation estimates from Lake Nasser. (a) 109 months at Raft station using BR values from Raft station. (b) 109 months at Raft station using BR values from Allaqi and Abusembel stations. (c) 58 months at Allaqi station. (d) 41 months at Abusembel station, averaged per month, as determined by the BREB method, 1995–2004. Error bars indicate the estimated maximum uncertainty (about 10%) of the BREB.

In warm tropical water, small temperature differences have disproportionately large effects on the density of consumers and hence on the stability of stratification (Talling, 1957). This study reveals that the upper 10-m layer represents the critical zone in physical, chemical, and biological activities along the water column during summer. In spite of a limited decrease in water temperature, that depth includes a noticeable variation in phytoplankton activity among the water column. It includes the peak of phytoplankton density, biomass (Chl *a*), and phaeopigments. It is also still well oxygenated. These parameters sharply declined downward.

In aquatic ecosystems, phytoplankton density, biomass, and photosynthetic capacity may indicate the eutrophic status of a lake. This study showed that depth profiles of phytoplankton standing crops are associated with water thermal stratification. Phytoplankton density is much greater in epilimnion than in hypolimnion. Epilimnion was turbulent, and phytoplankters are maintained in suspension in it. Reynolds (Reynolds, 1984) established that many cellular processes of phytoplankton are temperature-dependent, especially between 25°C and

40°C. Other physical, chemical, and biological (heterotrophic organisms) factors can affect the temporal distribution of phytoplankton in the lake's water. Grazer and predator populations may control phytoplankton populations directly and indirectly by large zooplankton, which can transport significant quantity of nutrients from the epilimnion layer (Longhurst and Harrison, 1988). Thus, regional variation of phytoplankton reflects its response to varying environmental conditions and is affected by advection, turbulence, and grazing, (Chang and Bradford, 1985).

Spatial and vertical distributions of net primary productivity in the lake water vary and reflect the response of phytoplankton to ecological variables. Values were limited between 31.9 and 74.4 mg C m⁻³ h⁻¹. The trend of its fluctuations in water column was irregular. Maximum production value was detected in surface water at El-Madiq and Korosko, whereas it was at 3 and 10 m at Kalabsha and Toshka, respectively. Integrated column productivity for the study depths revealed that Korosko was the highest productive area (947.8 mg C m⁻² h⁻¹), whereas El-Madiq was the lowest (713.9 mg C m⁻² h⁻¹). It was correlated with an equivalent concentration of Chl *a*.



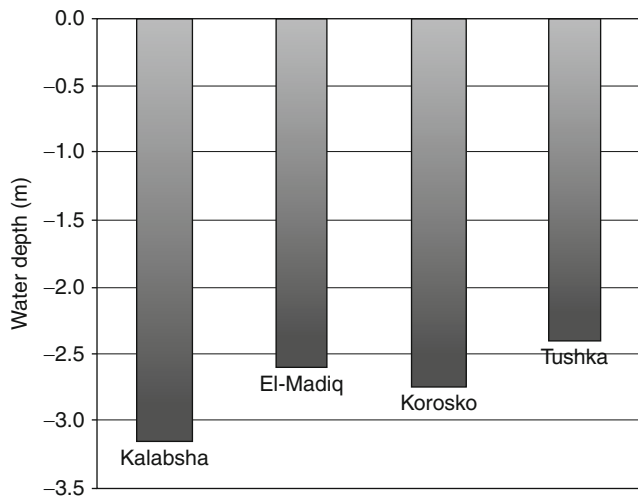
Nasser Lake, Figure 9 Sites for summer stratification.

Nasser Lake, Table 1 General morphometry of the studied sites in Lake Nasser at 160 and 180 m (above Sea level) water levels (cf. Bishai et al., 2000)

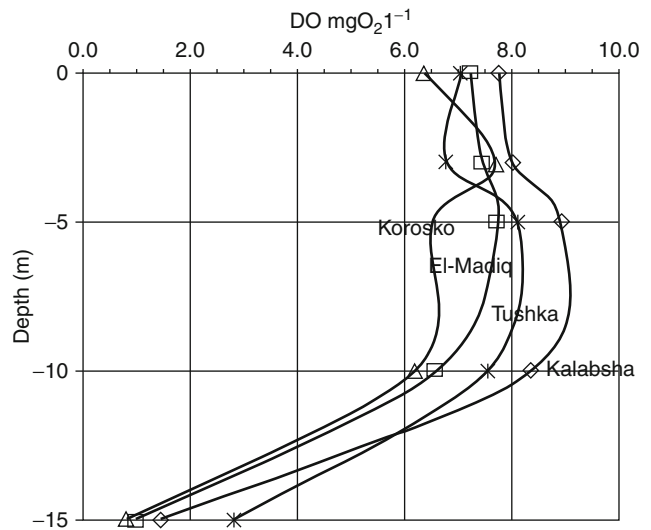
Site name	Distance from High Dam (km)	Length (km) at 160 and 180 m		Surface area (km ²) at 160 and 180 m		Perimeter (km) at 160 and 180 m		Maximum depth (m)
Kalabsha	46	22.0	47.2	54.0	620.0	85	517	40
El-Madiq	127	Main channel						54
Korosko	177	10.7	22.56	23.4	83.6	34	253	30
Tushka	245	24.1	33.35	49.1	366.8	89	127	20

Nasser Lake, Table 2 Temperature and dissolved oxygen amplitudes, and integrated values of some biological variables for water columns at the study sites in Lake Nasser during summer stratification

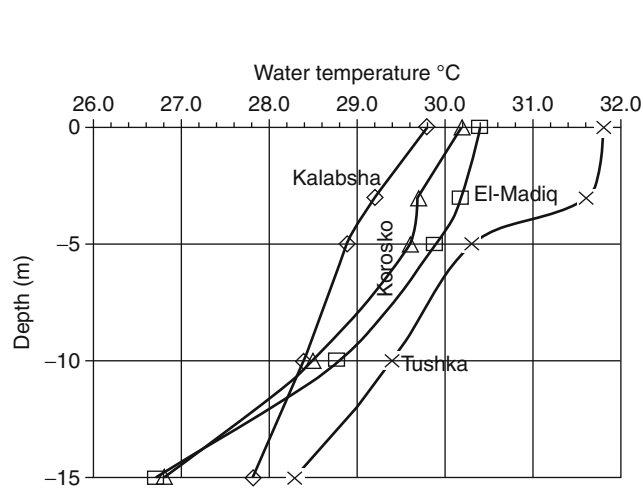
Site	Amplitude	Integrated value for depths per unit area (m^2)					
	Temperature ($^{\circ}\text{C}$)	Dissolved oxygen ($\text{mgO}_2\text{l}^{-1}$)	Chlorophylla (mg m^{-2})	Phaeophytin (mg m^{-2})	Primary productivity ($\text{mgC m}^{-2} \text{h}^{-1}$)	Assimilation rate ($\text{mgC mgChl}^{-1} \text{h}^{-1}$)	Standing crop ($\times 10^6 \text{ unit m}^{-2}$)
Kalabsha	8.2	7.491	238.9	677.0	257.1	22.0	1,713.7
El-Madiq	10.0	6.744	206.2	535.7	238.0	23.8	2,683.4
Korosko	9.9	6.878	247.0	667.9	315.9	24.4	2,886.0
Tushka	6.4	5.278	231.1	571.5	253.4	18.5	2,568.6



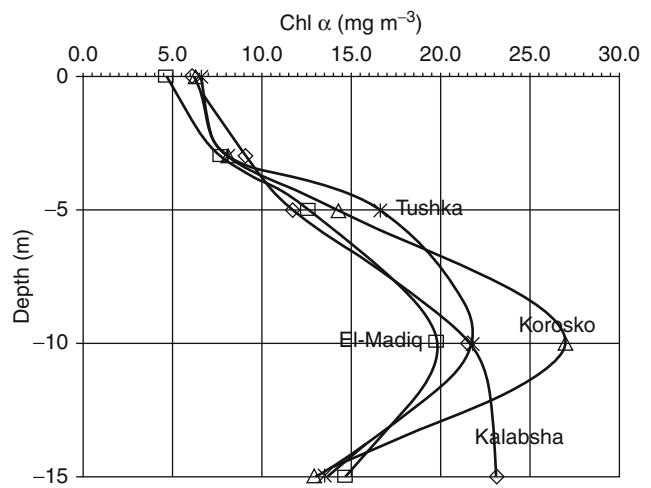
Nasser Lake, Figure 10 Water visibility at the studied sites.



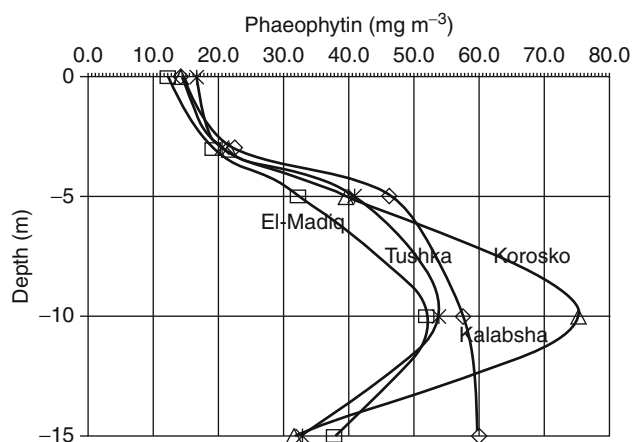
Nasser Lake, Figure 12 Depth profile of dissolved oxygen.



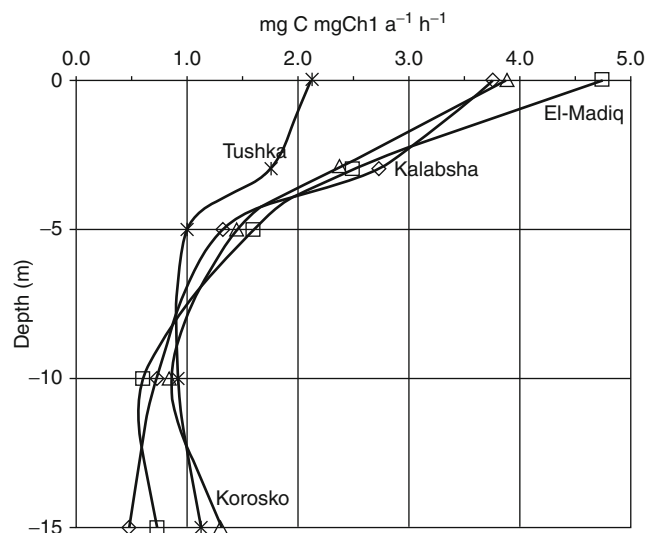
Nasser Lake, Figure 11 Depth profile of water temperature.



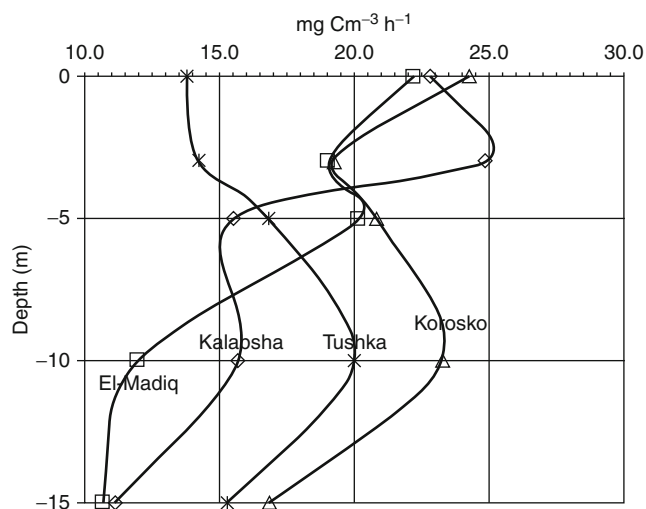
Nasser Lake, Figure 13 Depth profile of chlorophyll.



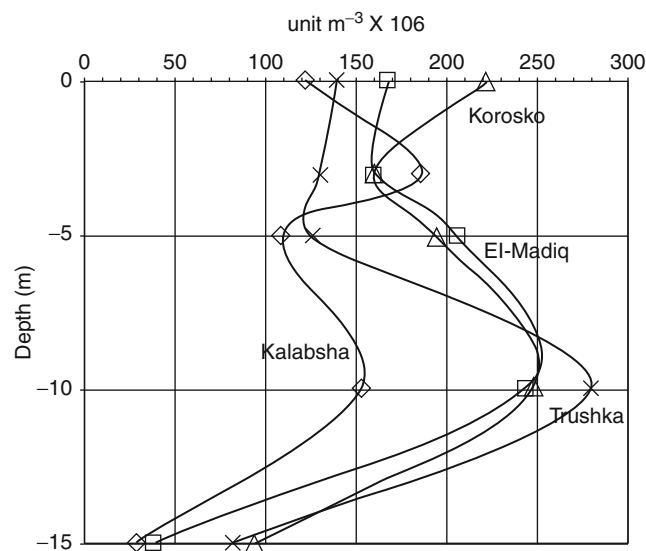
Nasser Lake, Figure 14 Depth profile of phaeophytin.



Nasser Lake, Figure 16 Depth profile of assimilation rate.



Nasser Lake, Figure 15 Depth profile of net primary productivity.

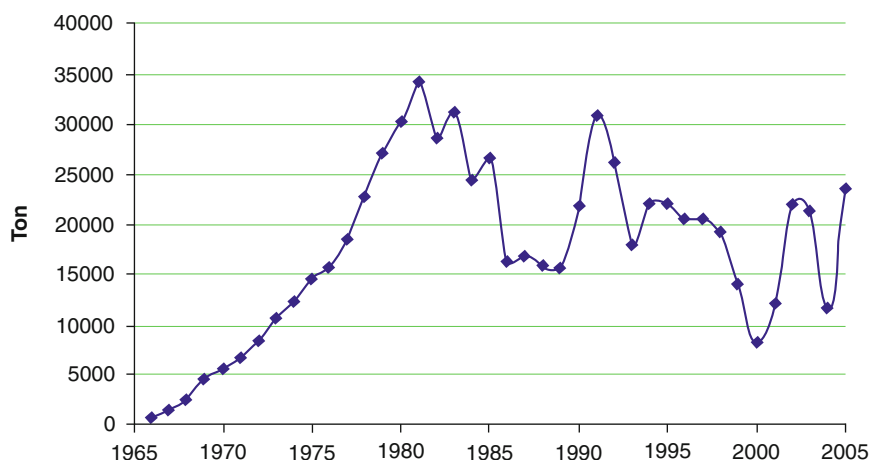


Nasser Lake, Figure 17 Depth profile of phytoplankton density.

Tilzer (1983) reported that light fractions absorbed by algae increase with biomass but decrease with rising inorganic turbidity.

Generally, variability of primary productivity in the given results cannot be related to specific factors. There may be a variety of factors controlling primary productivity, mostly abiotic in nature, such as light, climate, turbulence, and nutrients (Tilzer, 1983). It was mainly limited by light penetration (Secchi depth) and turbidity when nutrients are in excess of growth demands. Nevertheless, primary productivity control by the food web has been shown to be sometimes as influential as the aforementioned abiotic factors (Carpenter et al., 1987). Water movement can result in marked variations in interception

of light by phytoplankton (Grobbelaar and Stegmann, 1976). One therefore has to pay attention to other biotic components of the lacustrine ecosystem if a clear picture of the primary productivity is to be achieved. This is especially true for hypertrophic ecosystems where physical features are suspected to control primary productivity in view of nutrient excess (Roberts, 1984). Extensive human land use results in various levels of impact on actual net primary production. In a few regions, such as the Nile Valley, irrigation has resulted in a considerable increase in primary production (Haberl, 2007).



Nasser Lake, Figure 18 Fish Landing from Lake Nasser from 1965 to 2005 (Béné et al. 2009).

Fisheries production

Lake Nasser is one of the main sources of fishing in Egypt (Abd El-Monem, 2008; Entz and Latif, 1974; Béné et al., 2009). Variability of the entire studied parameters, in the water budget during summer stratification, are greatly affected on the seasonal distribution of fishes, and can be controlled on fisheries and fishing activities during the whole year. In addition, the expected fish yield and its sustainability can be expected from the primary productivity of the lake. Because Entz and Latif (1974) mentioned that fish usually avoid water layers containing less than 2 or 3 mg O₂ l⁻¹, and the same is true for fish food organisms. So fish searching for food usually avoid the hypolimnion, and choose the epilimnion for a habitat. But they even don't like that if the water temperature increases quickly. Therefore, most of them avoid the upper 1–2 m, and thus most of the fish may be located in summer time (during the stagnation period). Of course, there are typical littoral fish species that come to the very shallow water near the shore to find their best conditions for feeding. In winter, the fish spread throughout the lake water.

Fish landing from Lake Nasser from 1965 to 2005 is presented in Figure 18. The total fish landing increased with increase in water level in the lake from 1965 to 1981 to reach 35,000 t in 1981, then decreased again from 1981 to 1986 as a result of drought and subsequent decreases in the lake water level. Starting from 1986, fish landings showed abrupt changes that were not related to water level but due to price fixation and consequent smuggling of fish (Béné et al., 2009).

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Cross-references

Large Dams and Environment
 Large Dams, Statistics and Critical Review
 Mass Curve and Reservoir Design
 Nile Basin, Lakes
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NILE BASIN, LAKES

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Introduction

The Nile is the longest river in the world at about 6,700 km and extends over much of northeastern Africa, from 4° S to 32° N; it drains an area of nearly 3 million km². As Rushdi Said (1993) has shown, the basin is a relatively recent development; the longitudinal profile reveals a series of flat reaches in basins which evolved independently but are now linked by steep channels. The East African basin of the White Nile contains almost all the lakes of the Nile basin; it is relevant that this portion of the basin originally drained west toward the Congo.

Because the Nile basin is so extensive, the rainfall is extremely variable, both in terms of annual total and of seasonal distribution. The main areas where there is a surplus of rainfall over evaporation, giving rise to significant runoff, are the Lake Victoria and Albert basin in East Africa, and the western part of the Ethiopian highlands where average annual rainfall averages from 1,200 to 1,500 mm, and runoff is drained by the river Baro, the Blue Nile and its tributaries, and the Atbara. The major climate difference between these two areas is that the seasonal distribution of rainfall in the East African basin is bimodal, with rainfall seasons around April and November, while the Ethiopian basin has in general a single rainfall season around July–August. Because this effect is due to the annual migration from south to north of

the Intertropical Convergence Zone (ITCZ), there is also a transition between these two timings in the northern part of the Lake basin and the southern Ethiopian highlands. Because the Ethiopian highlands experience a long dry season as the converse of the single rainfall season, there is a smaller incidence of lakes in this region, and in fact, Lake Tana is the only major lake in this part of the Nile basin.

Within the East African lake region, the Nile basin contains a number of lakes of different types: Lake Victoria; the lakes of the Kagera basin and Lake Kyoga; and Lakes Albert, George and Edward. Their distribution and morphology depend largely on the geological history of the region, and it is necessary to describe this briefly.

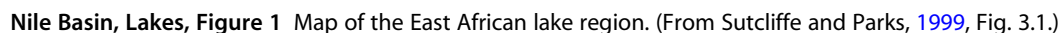
Geological background

The formation of the African Rift has had a major impact on the topography and drainage pattern of the upper White Nile basin in East Africa (Figure 1). Drainage from the Equatorial plateau toward the Congo basin was interrupted by the western arm of the Rift Valley, which gave rise to Lake Albert, Lake Edward, Lake Kivu, and Lake Tanganyika (the last two of which are outwith the Nile basin). In the same way the eastern arm of the Rift valley, which runs through Kenya and Ethiopia, gave rise to Lake Turkana and a number of lakes in central Ethiopia, and diverted the drainage of western Ethiopia, which had drained to the Indian Ocean, toward the Nile in the Sudan. Within the depression between the two arms of the Rift valley, Lake Victoria was formed as a close basin which overflowed at Jinja some 12,500 years ago, and several west-flowing rivers like the Kagera, the Kafu, and the Katonga were reversed in their course (Said, 1993). Figure 1 illustrates the fact that the Kafu and Katonga drain in two directions as a result of their diversion, and the shapes of the drainage pattern of the Kagera and its lakes and Lake Kyoga itself are also a result of this deformation.

The steep escarpment to the east of Lake Albert, and the mountains on the western or Congo flank of the lake, are indicative of its origin in the Rift Valley and form a contrast to the relatively flat surroundings of Lake Victoria and Lake Kyoga.

Water balance of lakes

Given that the rate of open water evaporation is primarily controlled by climate and is likely to be fairly constant over a region, the water balance of individual lakes depends largely on the amount and seasonal distribution of rainfall. There is evidence of variability over periods of years in the rainfall of the East African plateau, and there have been marked changes in the surplus runoff generated by the lake systems of the region. Such changes of regime are usually accompanied by rises in lake levels, and these rises draw attention to changes in the water balance. The most conspicuous example of such a regime change in recent years was the rise in Lake Victoria which



Although fluctuations in lake levels illustrate variations in the water balance of the system, these changes cannot be fully explained without adequate records or estimates of rainfall, evaporation, inflow and outflow, as well as water levels. Because the whole region was not developed until relatively recently, these records are only available for comparatively short periods, and are by no means complete in their coverage.

Available records

The East African lakes have only been known to the international community comparatively recently, as travel up the White Nile or Bahr el Jebel was prevented for many years by the presence of the swamps of the Sudd, which indeed means “barrier” in Arabic. The search for the source of the White Nile was a classic example of exploration during the nineteenth century, and Lake Victoria was reached by Speke from the East African coast in 1858. In 1862, Speke and Grant established that a large river flowed north out of Lake Victoria at Jinja. They then traveled north to reach Gondokoro on the Bahr el Jebel, where they met Baker, who reached Lake Albert in 1864 and established the connection between the Lake Victoria outfall through Lake Kyoga and Lake Albert to the Bahr el Jebel. Little time was wasted before scientific exploration began; Gordon mapped the course of the Bahr el Jebel in 1874, and although access through the Sudan was not possible between 1882 and 1898, climate data and water levels were recorded by Emin and others during this period.

Continuous lake water levels were measured around Lake Victoria from 1896, with a gap in 1897–1898, and these were converted to levels at Jinja (Figure 2), near the outflow channel. However, a number of earlier level observations were collected by Lyons during expeditions between 1899 and 1903, and published in Lyons (1906). By comparing these observations with levels derived from correlation with downstream flow records, a reasonable annual series of lake levels has been extended back to 1870 by Tate et al. (2001).

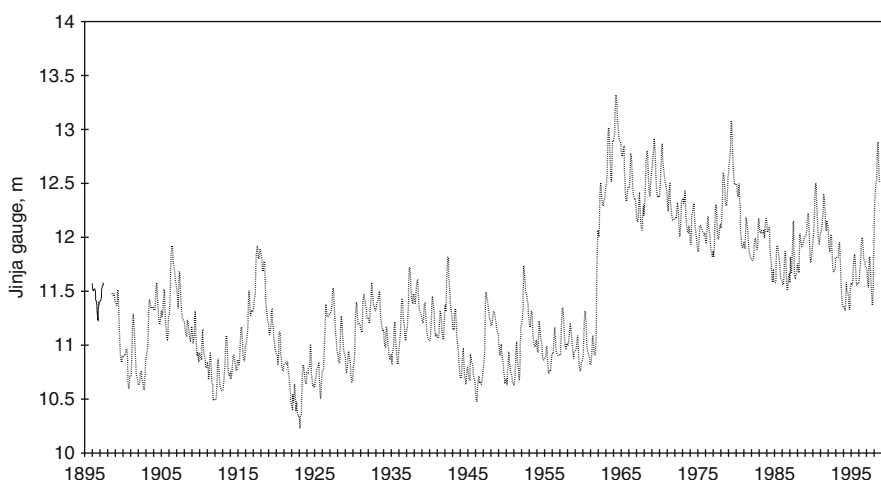
Similar lake level series have been maintained at Masindi Port on Lake Kyoga from 1912 and at Butiaba on Lake Albert since 1904. Levels are also available for Lake Edward between 1942 and 1978. These records reveal a similar pattern across the whole region, with an isolated rise around 1917 and a more sustained rise after

1961, which has been followed by a gradual fall interrupted by short rises in 1979 and 1997. Evidence from low flow periods at Aswan in Egypt, which depend on outflows from the East African lakes, confirms early observations that lake levels were high in the last quarter of the nineteenth century.

Records of rainfall in the East African basin, apart from observations at major sites, do not cover as long a period. However, there have been sufficient long-term stations around Lake Victoria for a number of attempts to derive a continuous series from 1925. The problem with using lakeside stations to deduce the rainfall occurring over the lake is that the lake is sufficiently large to create its own climate; indeed, Flohn and Burkhardt (1985) have memorably pointed out that the true source of the Nile is not the Ripon Falls or the highlands of Rwanda and Burundi, but the nocturnal cloud above the lake which provides the bulk of the lake inflow.

The establishment of gauging stations to measure river flow requires more organization than rainfall measurements. Although Hurst measured flows on several tributaries of the Kagera in 1926 (Hurst and Phillips, 1938), the Egyptian Irrigation Service began regular measurements of flows from 1940 though levels were measured from 1933. The inflows of the other Lake Victoria tributaries are available from various dates; four of the major tributaries are available from 1956, and almost complete tributary flows were obtained by the WMO Hydrometeorological Survey from 1969 to 1978. This Survey was established to investigate the causes of the rise in the lake system in 1961–1964.

Outflows from Lake Victoria are available from 1896, as the flows were controlled by the control at Ripon Falls, and the rating has been derived from discharges measured downstream and from hydraulic modeling. After the construction of the Owen Falls dam below the Ripon Falls, the outflow through the hydroelectric plant and



Nile Basin, Lakes, Figure 2 Lake Victoria monthly levels, 1896–1998. (From Sutcliffe and Parks, 1999, Fig. 3.2.)

spillway has been constrained to the natural outflow according to this “Agreed Curve.” Between Lake Kyoga and Lake Albert, flows are available at Masindi Port from 1912, and estimates have been derived at Kamdini from 1940, based on more reliable ratings (Sutcliffe and Parks, 1999).

Below Lake Albert, the most reliable flow records are at Mongalla on the Bahr el Jebel, which are available from 1905 to 1983 based on regular discharge measurements; however, these include the flows of the seasonal torrents which join the main river between Lake Albert and Mongalla.

Lake evaporation estimates have generally been based on Penman estimates of open water evaporation.

Water balance of successive lakes

Kagera basin

The Kagera is the main tributary contributing to Lake Victoria, and its basin contains a large number of small lakes. With a basin area of 60,000 km², the river, with its tributaries the Ruvuvu and Nyabarongo, drains much of Rwanda and Burundi as well as parts of Tanzania and Uganda. With a general elevation of 1,200–1,600 m, the basin rises above 2,500 m in the west, where peaks reach 4,500 m; the annual rainfall is less than 1,000 mm in the lower east of the basin, but rises to 1,800 mm in the higher west. A number of tributaries converge above Rusumo Falls, where regional warping and drainage reversal have led to valley courses filled with lakes or swamps totaling some 1,400 km².

There are two rainfall seasons, in February–May and September–November, and the runoff responds with a peak in April in the upper reaches, which is delayed by swamps and lakes to May at Rusumo Falls and July where the river enters Lake Victoria. The river passes extensive areas of swamps and lakes both above and below the falls, but it is easier to deduce the balance of the lower lakes and swamps, which cover about 1,600 km², by comparing inflows and outflows, rainfall, and evaporation (Figure 3). Figure 3a, comparing inflows and outflows for the lower lakes and swamp, shows the lag of about two months, while Figure 3b converts the water balance, including rainfall and evaporation over 1,600 km², into monthly lake levels which correspond with the observed fluctuations.

Lake Victoria

Lake Victoria is the largest lake in the Nile basin and covers an area of 67,000 km² with an average depth of 40 m; formed as it is at the center of the depression formed by the Rift Valley, it has a number of tributaries of which the Kagera is the largest. These drain a total area of 194,000 km² and contribute a total inflow of 23,000 m³ × 10⁶ or an average depth of only 120 mm over the basin; this inflow volume compares with a depth of 343 mm over the lake area. As this compares with an estimated annual rainfall over the lake of 1,858 mm, it is clear that the direct

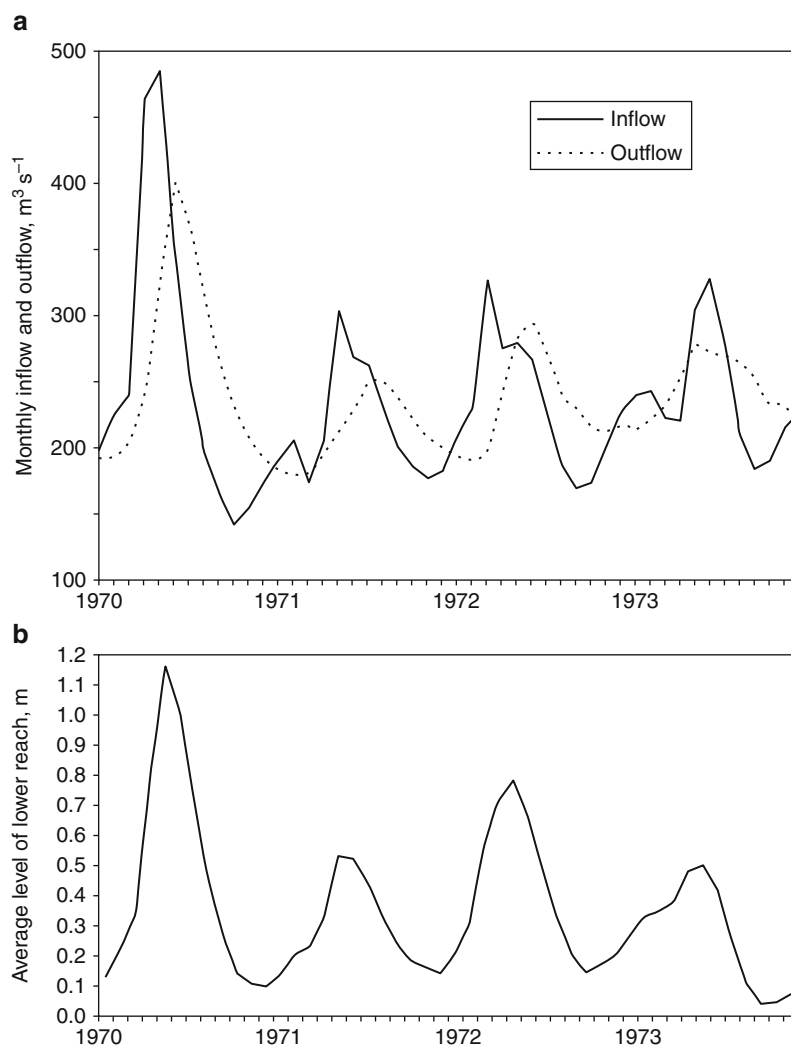
rainfall is the most important contribution to the lake water balance, but the tributary inflow is the most variable, because the runoff coefficient itself increases with rainfall. The water balance of the lake has been the subject of speculation and investigation over a number of years, but it was not until the inflow of the tributaries was measured after the establishment of the WMO Survey that reasonable estimates could be made, and the background to the unprecedented rise in lake level could be explained. The various components of the balance have been estimated for the period 1956–1978 with sufficient precision for this purpose.

The tributary inflow series has been completed by the Institute of Hydrology in 1985 (Piper et al., 1986) by comparing the almost complete flow measurements by the WMO Survey for the period 1969–1978 with the flows of four major tributaries for the longer period 1956–1978 and deriving monthly multipliers to deduce the total inflow for the whole period. The Kagera inflow, whose timing is different because of lake storage, was added separately.

The lake levels have been measured regularly at Jinja over this period, which includes the dramatic rise in the lake in 1961–1964. The changes in storage can be deduced from the lake area. The lake outflows can be deduced by applying the Agreed Curve linking lake levels with outflows, bearing in mind that the flows through the site were constrained to follow the curve after construction of the Owen Falls dam, where the turbine/sluice records provide an alternative estimate of outflows.

The lake evaporation forms a major portion of the outflow from the lake and, in fact, is similar in amount to the average rainfall on the lake surface. Because it is difficult to differentiate in practice between underestimation of rainfall and overestimation of evaporation, the choice of estimate is somewhat arbitrary. In the belief that variations from year to year would be small by comparison with variations in lake rainfall, the estimates of evaporation used by the Institute of Hydrology were based on monthly averages obtained by the Penman method for stations around the lake. The annual total was 1,858 mm.

The rainfall over the lake surface provides the major part, on average about 85% of the input to the lake water balance. It is not easy to estimate this rainfall as the only regular measurements have been made at stations around the lake perimeter. There are only eight stations with records from 1925 or earlier, and these records have been used by a number of investigators to estimate the rainfall input; the approach has the advantage of providing a reasonably homogeneous set of records of rainfall variations from year to year. The problem of estimation is made complex because evidence from the timing of rainfall incidence on the eastern and western shores, supported by some observations from rainfall stations on lake islands, suggests that rainfall over the lake itself is significantly higher than at the lakeside stations. The Institute of Hydrology used the lake itself to measure rainfall by a water balance approach; in 1993, direct



Nile Basin, Lakes, Figure 3 Kagera swamp below Rusumo Falls: (a) monthly inflows and outflows, 1970–1973; (b) deduced monthly water levels, 1970–1973. (From Sutcliffe and Parks, 1999, Fig. 3.4.)

comparison between the lakeside rainfall and net lake rainfall for calendar months in 1969–1978 suggested that they were linearly related, and this was used to derive a long rainfall series.

This rainfall series for the period 1956–1978, together with inflow and outflow totals expressed as depths over the lake surface, are included in Table 1. Further details of the balance study are given in Sutcliffe and Parks (1999).

When these components of the water balance are used in an annual water balance to estimate the changes in lake level, and these estimates are compared with measured levels, the correspondence is close. This is illustrated in Figure 4 for the period 1956–1978, when the records are most complete. This period covers the period of the rise in the lake, and its background is illustrated by the statistics of Table 1. Although the tributary inflow is small compared with the rainfall input, the tributary flow is comparatively

much more variable than the rainfall, because the runoff coefficient itself varies with rainfall. Because the average lake rainfall and evaporation are similar in total, the lake is very sensitive to an increase in tributary inflow. The doubling of the lake outflow after 1964 has had a significant effect on the lakes below Lake Victoria, but more significantly in the Bahr el Jebel wetlands of the southern Sudan where the swamps areas trebled in size.

It is worth noting that although the rise in lake level in 1961–1964 is unique within the period of measured lake levels from 1896, there is evidence from downstream flows and from early travelers (Tate et al., 2001) that the level was as high in 1878 and about 1892 though the return to lower levels was more rapid than after 1964. There is evidence from the southern Sudan that there was a period of high floods on the Bahr el Jebel after 1878, so the 1961–1964 event was not unique.

Lake Kyoga

The outflows from Lake Victoria, which reflect the bimodal nature of the rainfall on the lake itself (March–May and October–December) and on the tributary catchment, are attenuated by the large lake storage so that the seasonal peak monthly outflow in June is only about 15% higher than the low flow in November. The river, here called the Victoria Nile, flows for about 100 km below Jinja and reaches

Nile Basin, Lakes, Table 1 Annual water balance of Lake Victoria, 1956–1978 (After Sutcliffe and Parks, 1999, Table 3.3)

Year	Rainfall, mm	Inflow, mm	Outflow, mm	Level, m
1956	1,787	288	293	10.91
1957	1,727	270	300	11.02
1958	1,622	218	294	10.94
1959	1,702	199	275	10.84
1960	1,827	262	304	10.87
1961	2,370	326	307	11.94
1962	1,919	539	578	12.39
1963	2,121	517	668	12.91
1964	2,011	483	753	12.88
1965	1,663	269	700	12.48
1966	1,889	320	641	12.32
1967	1,752	320	565	12.31
1968	2,114	487	646	12.58
1969	1,770	315	687	12.36
1970	1,865	412	661	12.45
1971	1,639	301	590	12.17
1972	1,975	298	560	12.35
1973	1,749	298	574	12.05
1974	1,657	313	523	11.97
1975	1,826	283	497	12.04
1976	1,781	215	520	11.82
1977	1,938	435	537	12.13
1978	2,041	531	588	12.56
Mean	1,858	343	524	
Standard deviation	180	103	149	
Coefficient of variation (%)	9.7	30.1	28.4	

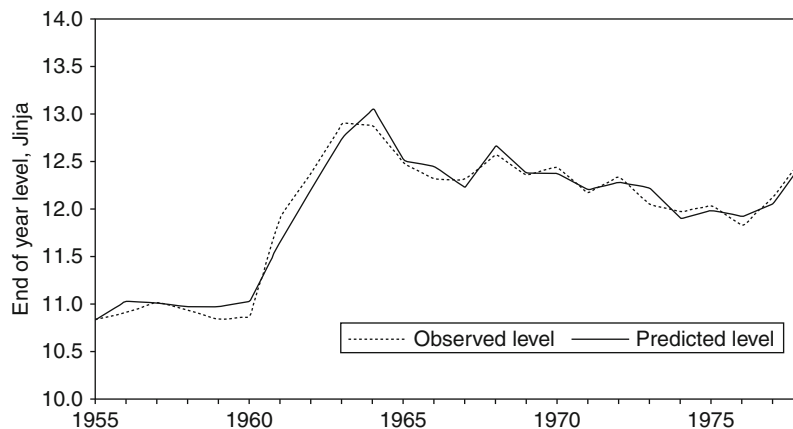
Lake Kyoga, which has the shape of a submerged river valley in an area of subdued relief. The lake is shallow, with a depth of about 3–5 m at its western end and shallower in its upstream arms. There is some uncertainty about the area of the lake and adjoining swamp, but a recent WMO estimate of 4,700 km² is reasonable.

Because the available records are largely confined to inflows and outflows in the main river, it is not easy to determine a complete water balance as local inflow is not measured consistently. Inflows in the main Nile are similar to outflows at Jinja, while lake outflows are available at Masindi Port from 1912, and more accurate measurements are available at Kamdini from 1940 to 1977 (Sutcliffe and Parks, 1999, Chapter 4). Local rainfall on the lake is about 1,300 mm compared with evaporation of about 1,600 mm. Comparison of inflows and outflows reveals that during the comparatively dry conditions before 1961, the channel inflows slightly exceeded outflows, suggesting that lake evaporation exceeded rainfall and local inflow. By contrast, after 1964, the outflows exceeded inflows, showing that local runoff and rainfall had increased to exceed lake evaporation. The annual net basin supply for the period 1940–1977 has been shown to be reasonably correlated with annual rainfall around the lake.

Lake Albert

Below Lake Kyoga, the course of the main river, here known as the Kyoga Nile, is influenced by the geological history of the region. The river turns up a former tributary of the Kafu below Masindi Port and then turns west to enter the Rift Valley and Lake Albert through the Murchison Falls. This lake is flanked by the Rift Valley escarpment on the east and by steep mountains on the western or Congo side of the lake. The lake is rectangular in shape with steep shores on its flanks and has an area of 5,300 km²; it reaches a depth of 50 m.

Lake levels have been measured at Butiaba, the port on the lake, from 1904 to 1981 (Figure 5). As would be expected, these records reflect the pattern of Lake Victoria



Nile Basin, Lakes, Figure 4 Lake Victoria annual water balance, 1956–1978. (From Sutcliffe and Parks 1999, Fig. 3.9.)

levels upstream, with the rise of 1917 being exceeded by the levels of 1961–1964; the fall in levels after 1964 has been more rapid than at Jinja. The water balance of Lake Albert is less well documented than the other lakes. The main inflow is carried by the main river, the Kyoga Nile, and has been measured at Kamdini for the period 1940–1977. A second tributary, the Semliki, drains a basin of 30,500 km² south of Lake Albert which includes the Ruwenzori Mountains and Lakes Edward and George; the flows of the Semliki have been measured at Bweramule from 1940 to 1978 at an average annual rate of 4.6 km³. There is additional local runoff estimated at 2.5 km³ from other streams which flow into Lake Albert.

Although attempts have been made to measure or estimate the immediate outflow from Lake Albert, the only long-term measurements below the lake have been carried out at Mongalla on the Bahr el Jebel. Flows at this site, where the main river enters the wetlands of the Sudd, have been measured from 1905 to 1983 with an annual average of 33.3 km³; however, these flows include the flow of the seasonal torrents which enter the river between Lake Albert and Mongalla; their estimated long-term annual measurement is 4.4 km³. Because the only long-term rainfall station near Lake Albert has been at Butiaba, with an average annual total of about 800 mm, there is likely to be a net evaporation loss from the lake. Although some of the elements of the lake water balance have had to be estimated, there is evidence (Sutcliffe and Parks, 1999) that the annual lake outflow and storage change minus inflow is related to Butiaba rainfall.

Balance of Lakes Victoria, Kyoga, and Albert

The overall balance of the successive lakes is indicated in Figure 6 where lake rainfall and local inflow are compared with lake evaporation and lake outflow for the years 1951–1960 (1956–1960 for Lake Victoria) and 1966–1975. Each component is estimated by various means

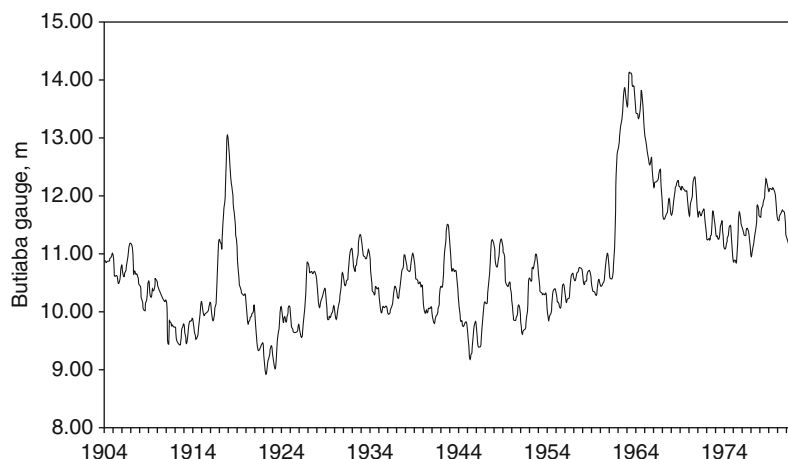
and is expressed as an annual volume (km³); the balance is not precise and discrepancies are partly explained by storage change. The figures demonstrate the importance of lake rainfall and evaporation in the case of Lake Victoria, and also the increased inflow in the later period. The dominance of Nile inflow and outflow in the balances of the lower lakes is apparent. The doubling of the overall outflow between the two periods is important, especially its effect on the Bahr el Jebel wetlands downstream. This increase was largely generated in the Lake Victoria basin, though the lower lake basins also contributed.

Lakes Edward and George

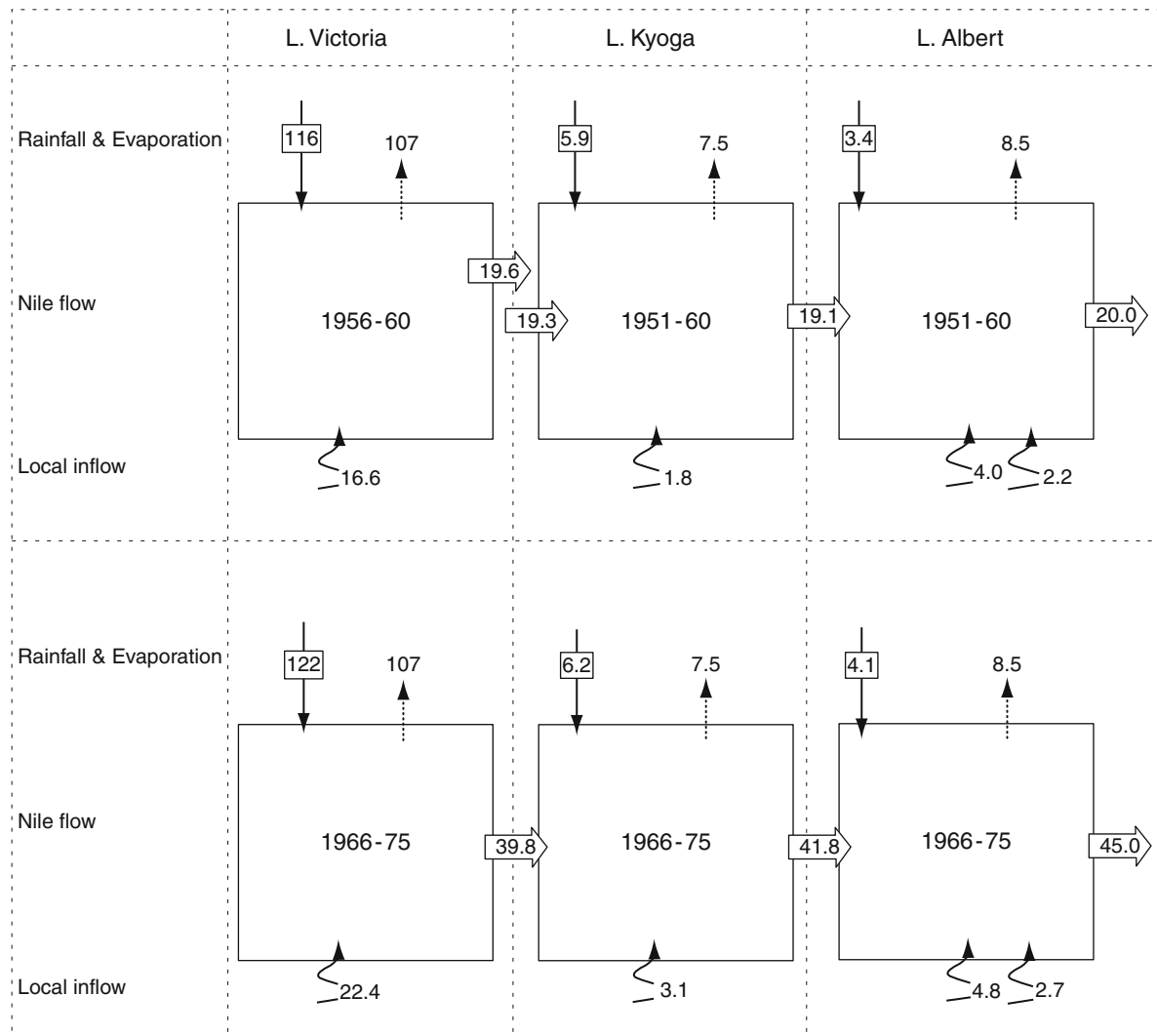
There are two further lakes in the Semliki basin above Lake Albert. Lake Edward (2,200 km²) and Lake George (300 km²) are connected by the Kazinga channel and receive inflow from the western channel of the Katonga and from a mountainous catchment. However, the main hydrological information is confined to lake levels on Lake Edward, measured from 1942 to 1978, which reveal a similar pattern to the other East African lakes, with a similar rise in 1961–1964 but a more rapid subsequent fall, and the flows of the Semliki measured above Lake Albert. These records do not permit a detailed water balance.

Lake Tana

The remaining major lake in the Nile basin is Lake Tana, which is situated at the upstream limit of the Blue Nile in Ethiopia. It was studied (Grabham and Black, 1925) as a possible site for reservoir storage and has been developed for hydroelectric power production. The lake has a surface area of about 3,000 km² at an elevation of 1,800 m. The basin draining to the lake is 13,750 km² and rises to nearly 4,000 m. The lake has many tributaries, with high and perennial, and highly seasonal runoff. The level range of the lake during this period was about 2 m; the shoreline contains a number of swamps dominated by *Cyperus papyrus*.



Nile Basin, Lakes, Figure 5 Lake Albert monthly levels, 1904–1983. (From Sutcliffe and Parks, 1999, Fig. 4.10.)



Nile Basin, Lakes, Figure 6 Schematic balance of Lakes Victoria, Kyoga, and Albert, $\text{km}^3 \text{ year}^{-1}$. (After Sutcliffe and Parks, 1999, Fig. 4.16.)

The Blue Nile leaves the lake through a series of cataracts, including the Tississat Falls with a drop of 50 m. Hydrological observations were carried out by the Egyptian authorities between 1920 and 1933; the mean annual outflow was 3.8 km^3 , or 7.8% of the long-term flow of the Blue Nile at Roseires.

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Cross-references

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NORTH DELTA LAKES, EGYPT

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Introduction

The Egyptian Mediterranean coast has five brackish lakes (Northern Delta lakes) which are situated along the Nile delta coast and to the east of the Suez Canal. These lakes are, from west to east, Maryut, Idku, Burullus, Manzala, and Bardawil (Figure 1). All except Lake Maryut are directly connected to the sea.

Lake Manzala is the largest of them with a total area of about 90,000 feddans and the depth rarely exceeds 2 m. Lake Burullus is the second largest Delta lake, with total area of about 70,000 fed. and an average depth of 1.2 m. Lake Idku is situated approximately 35 km east of Alexandria. It is a shallow eutrophic lake rarely exceeding 1.5 m in depth. Lake Mariut is the smallest of the Delta lakes, occupying about 17,000 fed. It is actually isolated from the open sea. The depth ranges from 0.6 to 2.7 m.

The Northern Delta lakes provide a rich and vital habitat for estuarine and marine fish and their regeneration and have always been major areas of fish production in Egypt, where more than 75% of Egyptian lakes production was harvested from them (Mehanna, 2008). Also, they are internationally important sites for wintering water birds, providing valuable habitat for several hundred thousand

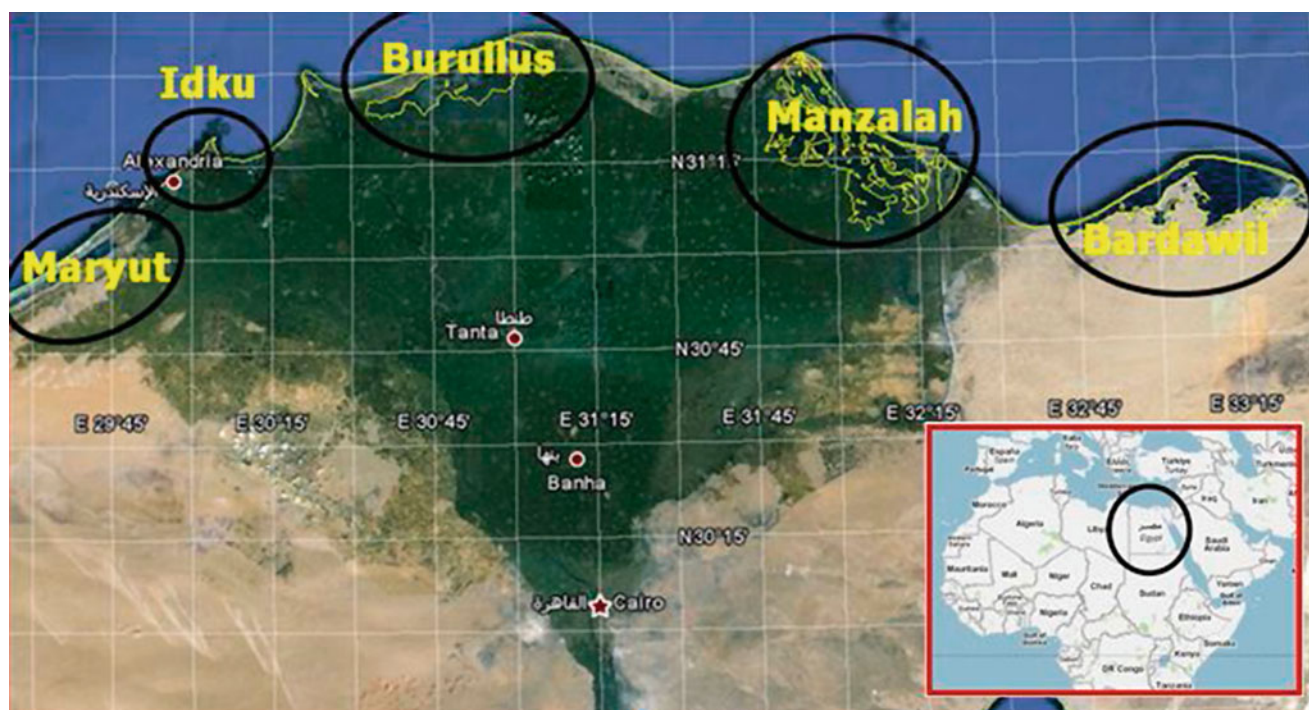
birds. In recent years, these lakes are facing many challenges, leading to the depletion of fish production from them (Figure 2).

Degradation, habitat loss, filling up, and drought which lead to decreasing the area of all Delta lakes by more than 70% of their origin areas. Delta lakes are the most polluted areas in Egypt. They receive great amounts of industrial, municipal, and agricultural wastewater without treatment. Spread of aquatic plants which covered large areas from these lakes. Over-fishing, illegal fishing practices, and illegal harvesting of fish fry. The blockage of Boughazes (the connections with open sea). High levels of eutrophication resulting from the increased nutrient influx from agricultural drains carrying large amount of washed and leached fertilizers and pesticides.

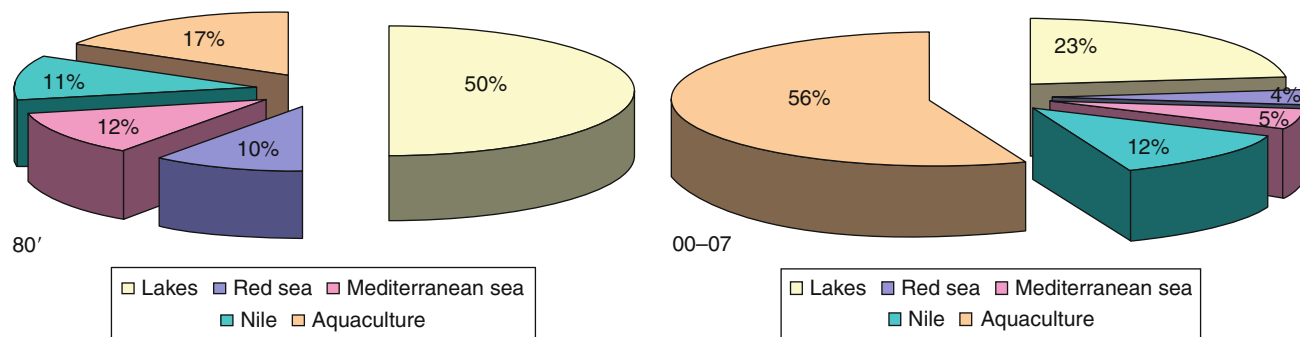
The present research shows the main features of the five Northern Delta Lakes (Maryut, Idku, Burullus, Manzala, and Bardawil).

Burullus Lake

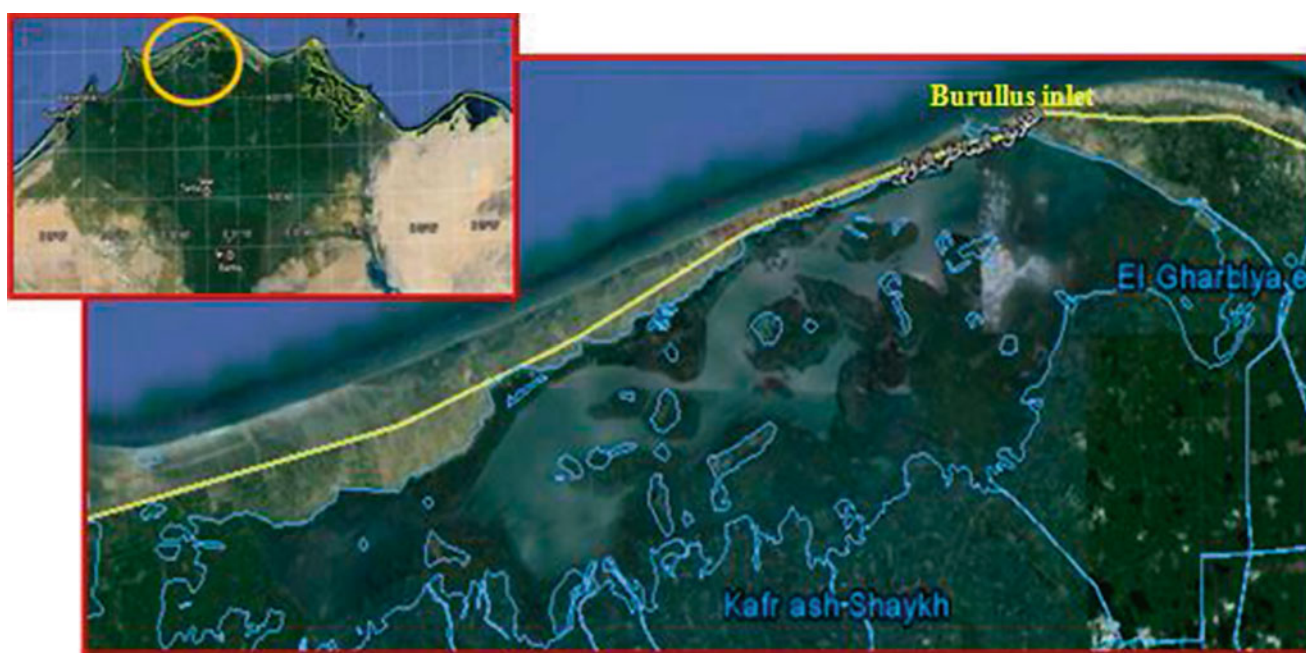
Burullus is the second largest lake of the Nile delta coastal lakes. It is connected to the sea at its northeastern edge through the Burullus inlet, which is about 250 m wide and 5 m deep, (Figure 3). It is about 53 km long, 13 km wide, and has water depths ranging from 0.5 to 2.5 m (Frihy and Dewidar, 1993) (Figure 4). The northern border is separated from the Mediterranean Sea by a strip of land covered with sand bars and dunes. Seven drains and freshwater canals are connected to its eastern, southern, and



North Delta Lakes, Egypt, Figure 1 Northern Delta Lakes, Egypt.



North Delta Lakes, Egypt, Figure 2 Fisheries resources of Egypt during the 1980 compared with those of the last 8 years. (After Mehanna, 2008.)



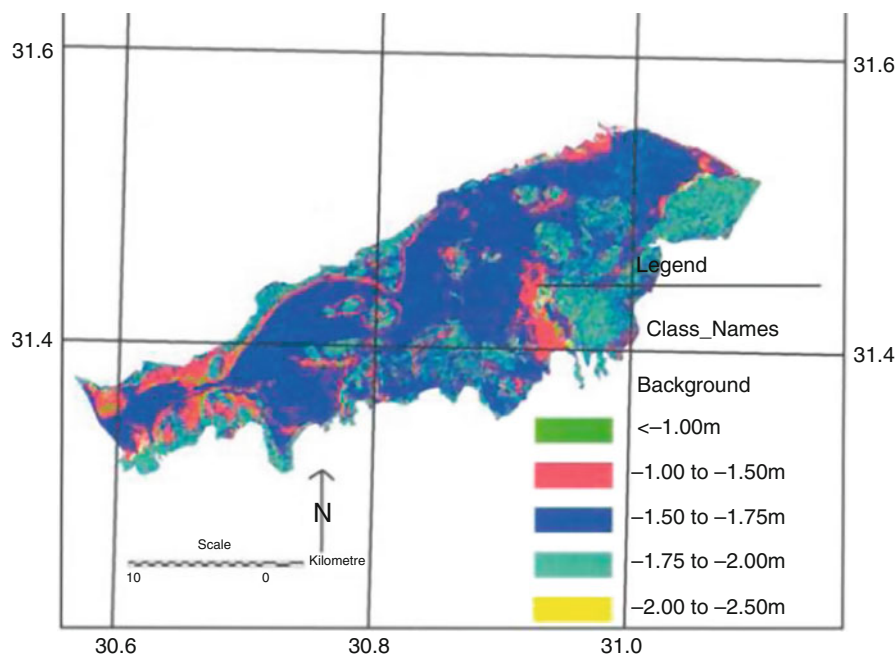
North Delta Lakes, Egypt, Figure 3 Burullus Lake, Egypt.

western shores. The lake barriers are sandy and range from 0.4 to 5.5 km in width. They are generally <1.5 m above mean sea level, with beach face slopes ranging between 5° and 13°. Low relief backshore and fore dunes characterize the western barrier. The eastern barrier is narrow and backed by barchans coastal dunes. These dunes encroach landward onto a cultivated coastal flat. Water is discharged into the lake through a series of seven land drains. The estuarine water of the Rosetta mouth of the Nile River is also connected to the lake water through the Brimbal Canal. These water sources and other (rainfall and seepage of underground water) cause the rise in the lake level, inducing a lake sea current (Saad, 1990).

Several studies have been carried out on the different aspects of the lake ecology (El Sabrouti, 1984; Saad,

1988; Abdel Moneim et al., 1990; Fatouh, 1990; Maiyza, et al., 1991; Shakweer et al., 1998). These results showed that the water quality of the lake has changed over time. These changes are related to human intervention and eutrophication processes. The bottom sediments of the lake are predominantly silty clay, with high organic content in parts and large areas of shelly to silty, muddy sand (Coutlier and Stanley, 1987). Approximately 75 islands are scattered in Burullus Lake with varying surface areas, and they comprise a variety of habitat types. Several studies indicated that the size and shape of Burullus Lake has changed due to a shrinking, resulting in increase in island size (Khedr, 1999).

The spatial distribution of sand and organic matter values is consistent with the results of Coutlier and Stanley



North Delta Lakes, Egypt, Figure 4 Bathymetry map of Burullus Lake. (After, Frihy and Dewidar, 1993.)

(1987) which indicated that the texture of bottom sediments is modified from silty clay, with high organic content in parts and large areas of shelly to silty muddy sand (Figures 5 and 6).

The salinity values are higher than 5,000 mg/l for most of the lake parts. At the western and southern part of the lake, the salinity levels are lower than 1,000 mg/l (Figure 7). The main causes are the lake's nearness to the freshwater resource from Rosetta branch of the Nile River (Brimbal Canal) and the inflow of drainage water from southern drains.

According to Fanos (1992), the tide at El-Burullus headland is estimated as the difference between the mean high water level (33 cm) and the mean low water level (18 cm). Fanos (1992) considered the difference (15 cm) as small and concluded that the tidal effect is small. Accordingly, the tidal effect has been neglected. El-Shinnawy (2003), Rainfall data recorded at Al-Burullus lighthouse (31°36'N, 31°05'E) for a period of 81 years (1912–1992) has been collected and examined. Monthly records of rainfall data have been treated and statistically analyzed. Mean monthly values have been estimated and illustrated in Figure 8. The mean annual depth of rainfall is 187.37 mm. This depth of water provides the wetland with a mean annual volume of about 77.35 million cubic meters.

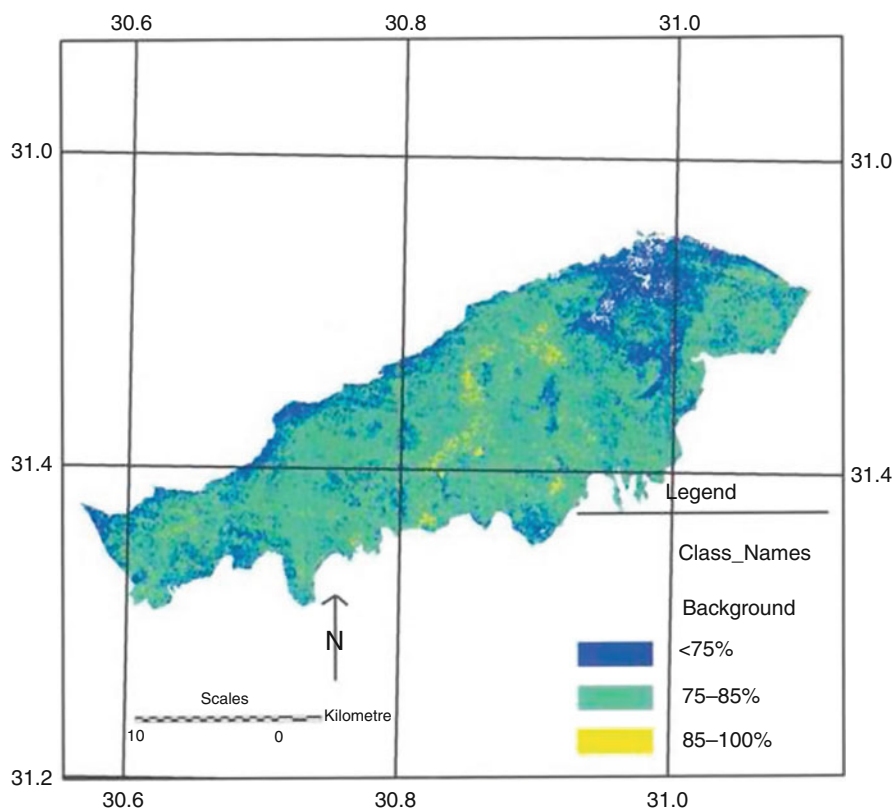
Evaporation measurements at adjacent stations in Port Said and Alexandria localities have been collected and analyzed. An average value for daily and monthly evaporation at the study area in each month was estimated as presented in Table 1.

Bardawil Lake

Bardawil Lagoon is located at the southeastern Mediterranean coast at 31°09'N, 33°08'E (Figure 9). It is an oasis for migrating birds as well as a Zaranik protected area (Anonymous, 2005), an important source for economical fish and salt production (Abd Elrazek et al., 2006; El Shaer, 2008), and a high diversity of habitat for wildlife (Touliabah et al., 2002). The lagoon is nearly clear and it is the least polluted in the entire Mediterranean region (Arvanitidis et al., 2009). The Bardawil lagoon represents a transitional zone between land and sea and it is separated from the Mediterranean Sea along most of its length by a long and narrow sand bar. It is connected to the sea via three narrow artificial inlets (Figure 10). Two of them are man made (western and eastern inlets), while the third one has been naturally closed (El-Shabrawy, 2006). The lagoon extends along the coast, and so it has a micro tidal regime. The Mediterranean Sea tides govern water exchange in the lagoon and have a mean tidal excursion of 25 cm during neap tides and about 35 cm during spring tides (Moursy, 1994).

Bardawil lagoon suffers from many problems, which might lead to environment degradation, shortage in fish catch, and substantial changes in its ecosystem. Drying up of some areas inside the lagoon and subsequently loss of its biological and economic values is due to the frequent changes in inlets' form and dimension. An extensive salt production system (constructed in the eastern part) leads to considerable ecological changes.

There are many investments around the lagoon, like tourism developments. There is a large-scale agriculture



North Delta Lakes, Egypt, Figure 5 Distribution of sand% for Burullus. (After, Dewidar et al., 2005.)

reclamation project in North Sinai near the lagoon; the inflow of freshwater from the new reclamation lands will change the lagoon from a saline to brackish lagoon, leading to the deterioration of water quality (Mageed, 2006); otherwise, Bardawil Lagoon development, including urbanization and lagoon engineering such as artificial inlets, promotes some undesirable changes in its system. Radwan et al. (2009) carried out a study to evaluate Bardawil Lagoon from a physical limnology point of view, through investigation of its climate, bathymetry and morphometrical features, and monthly and annual changes in salinity.

Bardawil has shallow water with irregular bottom topography. Figure 11 shows the lowest water depth (0.3 m) and the highest (6.5 m) recorded at the extreme eastern region (Zaranik area) and inside the inlets, respectively. The average water depth inside Bardawil Lagoon is around 1.21 m. The Lake bottom is composed of sand and silt (Levy, 1971).

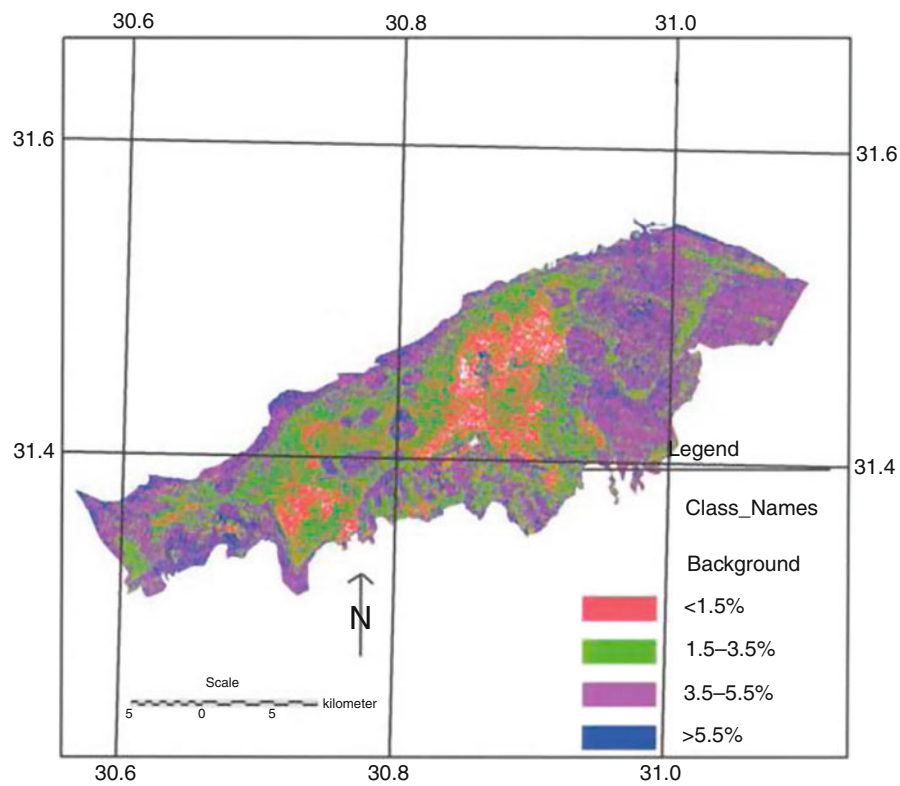
Air and water temperatures of Bardawil Lagoon are low in winter and high in summer (13.7–27.0°C and 13.9–24.6°C, respectively). Winds blow from all directions, but most abundantly from the north most of the time. The recorded wind speed shows great variability from a month to another ranging between 4.5 and 6.3 m/s. The relative humidity varied between 48.5% and 57.1%.

Evaporation rate is low in winter and high in summer (3.23–6.0 mm/day), (Figure 12).

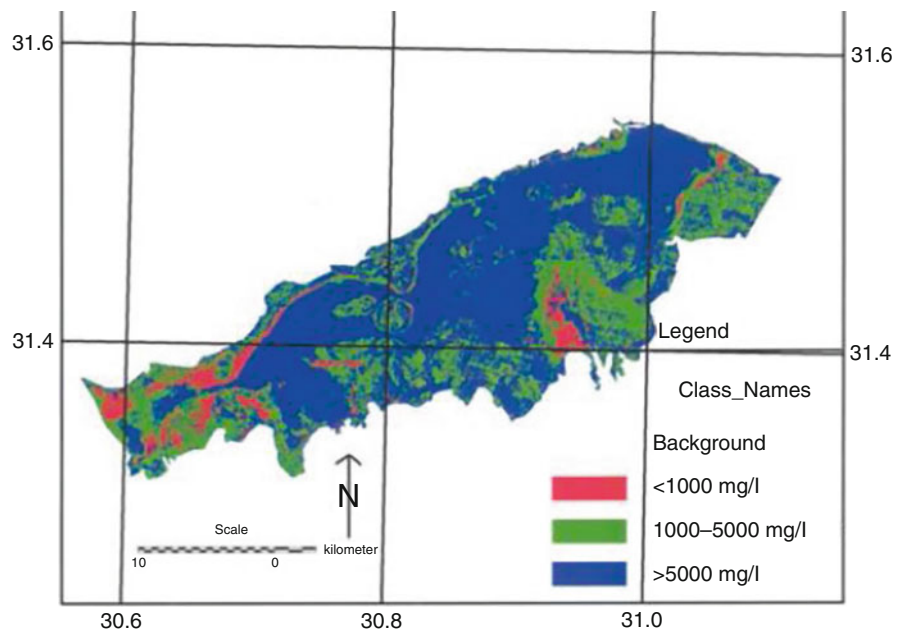
Figure 13 illustrates spatial and temporal water salinity distributions inside the Lagoon. From the salinity results it could be concluded that there is a high fluctuation in the salinity range, the lowest value is 38.3‰ and the highest is 71.1‰.

Lake Manzalah

Lake Manzalah is almost rectangular in shape with a long axis running from the northwest to the southeast (Figure 14). It is connected to the Mediterranean Sea through the main opening at Al-Gameel region, west of Port Said, and it is connected with the Suez Canal through a small canal at Al-Gabouty near Port Said. Highly productive freshwaters of the Nile enrich the Lake through three canals originating from the Damietta Branch: Al-Enania, Al-Rotma, and Al-Sufara canals. The Lake is enriched by drainage water transported by five main drains which are connected to the Lake at the south and southeastern borders (Figure 15). These drains are Al-Serw, Al-Gamaliah, Bahr Hadus, Ramsis, and Bahr-Bagar. Malati (1960) mentioned 1,022 islets with a total area of 3,137 feddans. These islets divide the Lake into about 30 basins. Most of these islets are inhabited by fishermen and farmers.



North Delta Lakes, Egypt, Figure 6 Distribution of organic matter% for Burullus. (After, Dewidar et al., [2005](#).)



North Delta Lakes, Egypt, Figure 7 Salinity distribution for Burullus Lake. (After, Dewidar et al., [2005](#).)

At the beginning of the twentieth century, the surface area of the Lake was about 420,000 feddans. Because of the continuous processes of land reclamation for agriculture, the area has gradually decreased reaching in 1980 to about 200,000 feddans (Macleren, 1981). In fact, Lake Manzalah is affected by various external factors, the most important of which is the progressive increasing of industrial and agricultural wastewater discharge.

The bottom of Lake Manzalah is covered with silty clay and sandy silty clay in the southern part. The western and southwestern regions have bottoms covered with silty clay. The central regions of the Lake are mainly covered with clayed sand (El-Wakeel and Wahby, 1970b). Further to the northeast, the Lake bottom is composed of silty clay.

The Lake bottom is contaminated with different accumulations of lamellibranches. Three regions constituting the bulk of Lake Manzalah were described by El-Wakeel and Wahby (1970a) as follows: (a) Southeastern region, which receives its water from Hadus and Bahr El-Bagar drains; (b) the second region extending along the route connecting Mataria to Port Said; and (c) the third region occupying the western side of the Lake, which receives freshwater from the Sufara, Ratma, and Enaniya canals. This area is affected also by the water coming from Faraskour Barrage. Guerguess (1979) found in Lake Manzalah that the minimum pH values were recorded at this area where it varied between 7.0 and 7.80 with an average of 7.46. He attributed the decrease of pH values

to the high rates of wastewater discharge from three drains at this polluted region.

The direction and speed of blowing winds as well as the chemical properties of wastes discharged into the Lake are the most important factors affecting the chemistry of Lake Manzalah waters. The strong northern winds blowing steadily from March to September pile up the sea water along the coast resulting in rising sea level and may contribute in transporting the sea water into the Lake. The directions and speeds of winds blowing on Lake Manzalah during the whole year can be briefly indicated as follows:

During *winter* season the winds at Port Said blow mostly from NE, NW, and SW, with velocities from 1 to 21 knots, mostly from 4 to 10 knots

During *spring* season the winds blow mostly from NW, less from SE and S, with velocities ranging from 1 to 21 knots, moderately from 4 to 6 knots.

The *summer* season is characterized by calm winds (NW), with velocities from 1 to 16 knots, moderately from 1 to 3 knots NW winds.

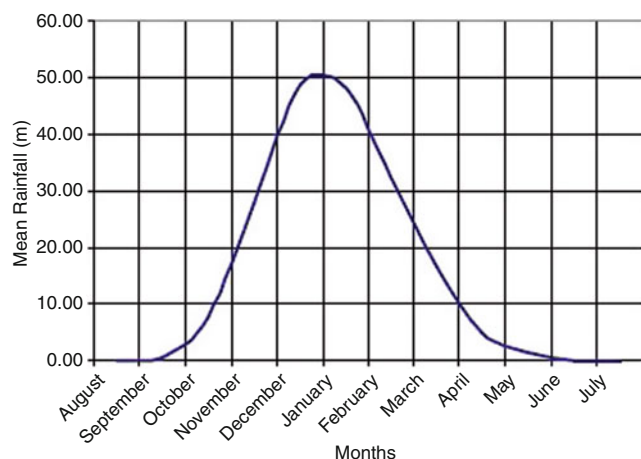
During *autumn*, the winds blow mostly from NW and NE, with velocities ranging from 1 to 16 knots, and moderately from 4 to 6 knots.

Due to the shallowness of Lake Manzalah together with the common mixing of water by wind, the thermal stratification was difficult to be established in the water body of the Lake (Wahby et al., 1972). The recorded water temperature at the various sampling stations are given in Tables 1 to 6 and graphically shown in Figure 16.

It can be observed from the data given that:

- The minimum water temperature was recorded during January when water temperature ranged from 11.0°C to 13.0°C, this agrees with El-Araby (1990)
- The maximum water temperature was recorded during July ranging between 27.0°C and 30.0°C with an average of 29.0°C, as recorded by El-Araby (1990)
- The water temperature started to increase gradually from February to reach the maximum in July where it began to decrease gradually reaching its minimum in January
- The difference in water temperature did not exhibit large values from one station to another

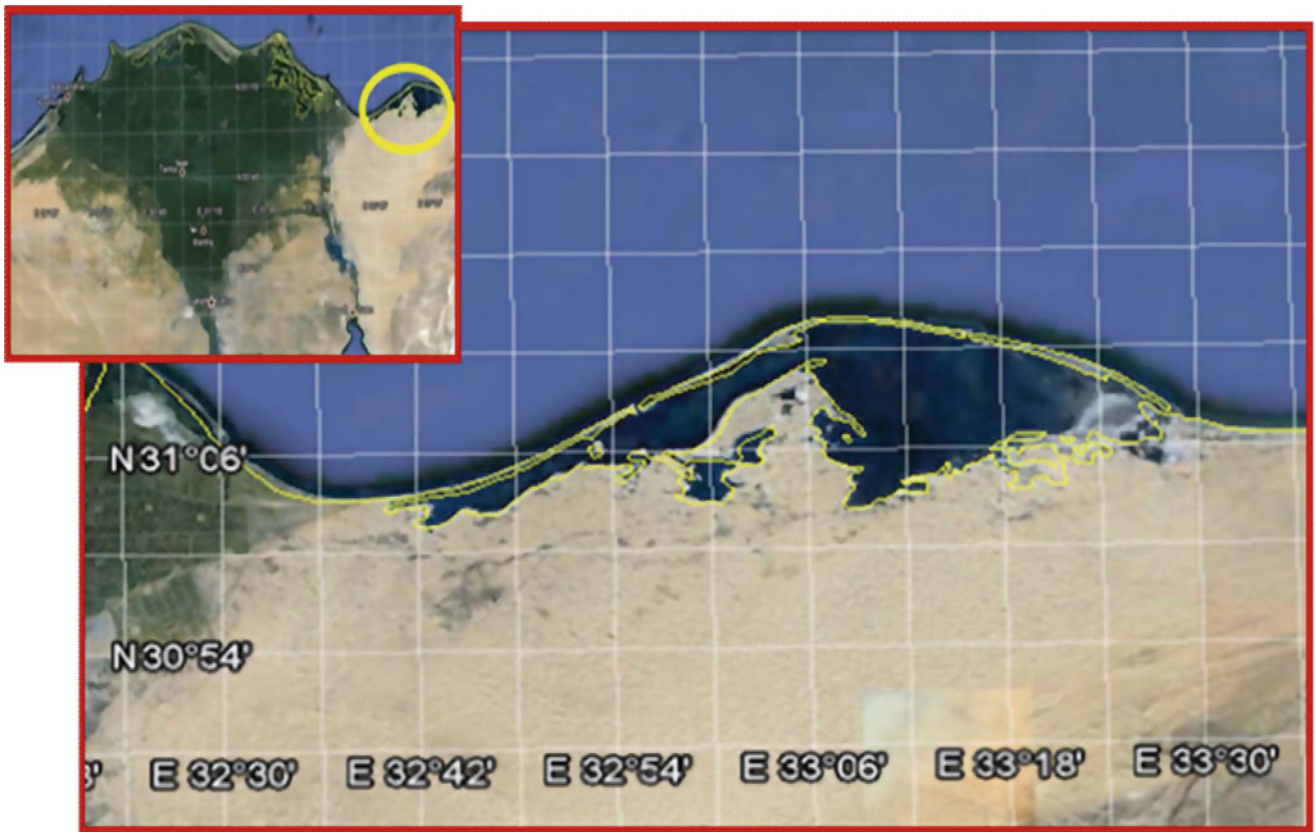
Beside temperature effect on the chemical and physical characteristics of the environment, it has a great effect on the vital activities of the living organisms. Temperature influences the total standing crop of phytoplankton where it decreases during winter and regains its maximum during spring and summer. Dissolved oxygen as well is influenced by temperature, since reverse correlation exists



North Delta Lakes, Egypt, Figure 8 Mean monthly rainfall over the wetland. (After, El-Shinnawy, 2003.)

North Delta Lakes, Egypt, Table 1 Average monthly evaporation volumes at Al-Burullus wetland (10^6 m^3). (After, El-Shinnawy, 2003.)

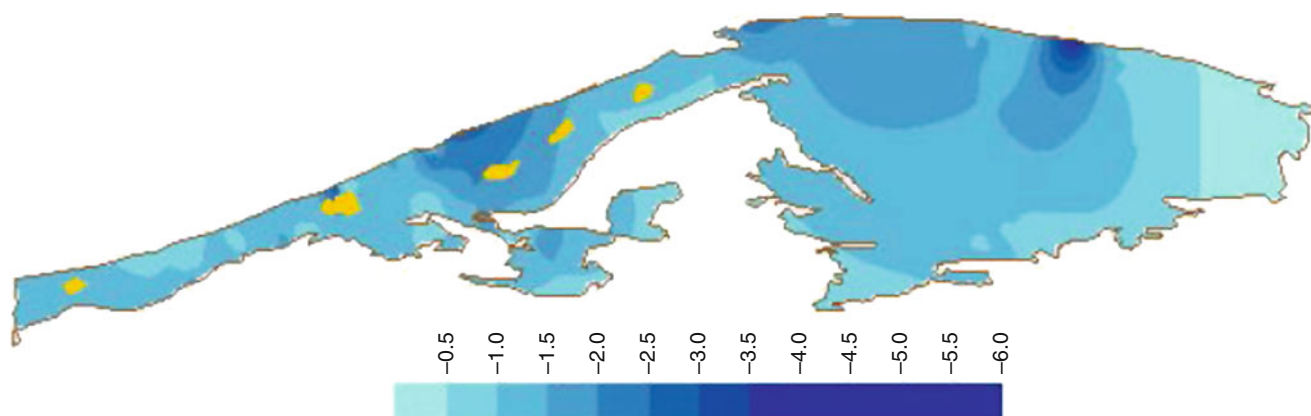
Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean Volume	454	44.7	53.5	54.4	62.3	58.7	60.4	59.2	57.3	55	48.6	47



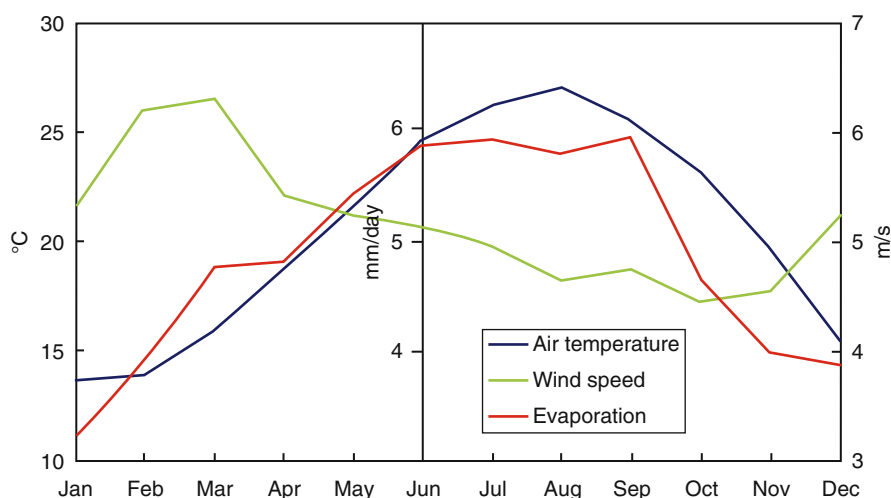
North Delta Lakes, Egypt, Figure 9 Bardawil Lake, Egypt.



North Delta Lakes, Egypt, Figure 10 Bardawil Lake inlets, Egypt.



North Delta Lakes, Egypt, Figure 11 The bathymetric map of Bardawi Lagoon. (After, Radwan et al., 2009.)



North Delta Lakes, Egypt, Figure 12 Air temperature, wind speed, and rate of evaporation in Bradawi Lagoon. (After, Radwan et al., 2009.)

between dissolved oxygen and temperature (Saad, 1987). Prepas and Trew (1983) found that temperature influences on phosphorus release increase in summer. In addition, it is well known that fish is sensitive to temperature variations. The minimum water temperature was recorded with an average of 12.35°C in January while the maximum was 29.14°C in July.

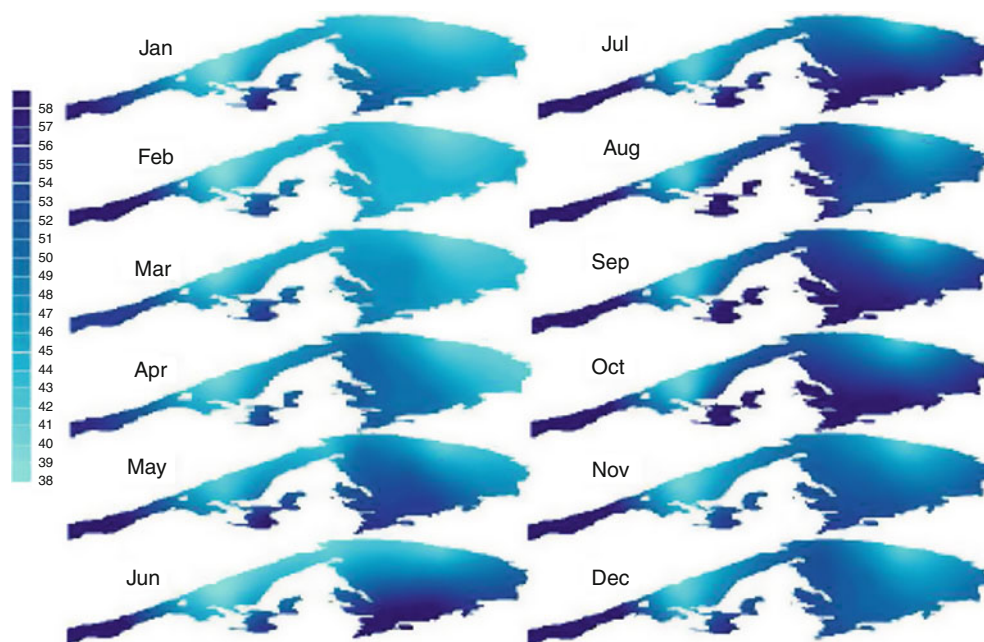
The evaporation accelerated by the high summer temperature as well as the rain water are other factors influencing the total dissolved solids (TDS) in the lake.

The effect of increasing human activities, mainly industrial, agricultural, and mariculture carried out at the areas adjacent to Lake Manzalah, on the Salinity of N.E. area, was observed. The values of salinity and TDS during 1967 (Youssef, 1967, 1975, El-Araby, 1990; Shakweer, 2005) are given in Table 2. The data given indicate that

El-Gamil area exhibits steady decrease of water salinity where its average value decreased from 17.24‰ to 5.37‰ in 1975 and to 2.53 g l⁻¹ in 2001. This region, though was characterized by high rates of primary and fish production, is suffering now from drastic water pollution and decreased rates of fish production.

Maryut Lake

Lake Maryut is the westernmost of the northern delta wetlands (31°07'N/29°53'E), although its history and origin are different (Figure 17). Formerly, the lake was fairly large, but late in the nineteenth century the western half was cut off by a railway embankment and transformed into an extensive salina, now known as Malahet Maryut, which is seasonally flooded (usually during winter). Today, the remaining part of this lake is made up of several



North Delta Lakes, Egypt, Figure 13 The spatial and monthly variation of the water salinity in Bardawil Lagoon. (After, Radwan et al., 2009.)

fragments, dissected by roads and embankments, and lies practically within the boundaries of greater Alexandria and its sprawling suburbs.

What remains of the lake proper is brackish, receiving agricultural drainage water through several drains (the most important of these is the Qala Drain), as well as large quantities of municipal and industrial effluent from the city of Alexandria. The lake has no direct connection with the Mediterranean, and it is maintained at a level of c. 2.8 m below sea-level by a pumping station at El Max. Much of the lake shore is fringed by extensive *Typha/Phragmites* marshes. The lake still supports a fishery, with *Tilapia* sp. making up most of the production.

By the end of the nineteenth century, the development of irrigation systems of the adjacent fields made Lake Mariut an intermediate water body to receive the excess of water from the irrigation channels. Then the water was pumped out to the Alexandria Bay. Lake Mariut, for a long time, represents a source of fish production in Egypt. Currently, some parts of the lake are used in aquaculture activities. The *Tilapia* sp. is of considerable importance in fisheries of Lake Mariut as it represents about 90% of the total catch in the lake (Bakhoum, 1994).

Nowadays the lake occupies around 250 km² due to intense land reclamation for urban and agricultural purposes. The life of Lake inhabitants continues to be carried on in much the same way as in ancient times, but now the reed masses cover more than 50% of the lake and fisheries richness has declined both in volume of catches and in fish quality. The Lake is artificially subdivided into four basins

(Figure 18); Main Basin, Aquaculture Basin, Southwest Basin, and Southeast Basin – Main Basin: 25 km² (6,000 feddans), Fisheries Basin: 4.2 km² (1,000 feddans), Northwest Basin: 12.5 km² (3,000 feddans), Southwest Basin: 31.5 km² (7,000 feddans).

Unfortunately, Lake Mariut suffers from almost all possible environmental problems and to quite an extreme degree. Land filling for building houses, infrastructures, and agriculture has reduced the area of the Lake from 700 km² to the present 250 km². These three human activities have critical impacts on the remaining area of the Lake. Pollutants load has been estimated at 122.6 t/day for sanitary drainage, 180 t/day from industries, and up to 6 million m³/day of agricultural wastewaters. All these inputs introduce in the Lake huge amounts of inorganic and organic toxic substances, such as different forms of nitrogen, phosphorus, heavy metals, pesticides, and pathogens. Urban expansion from the densely populated Alexandria and the uncontrolled deposition of solid waste complete a very complicated and distressing environmental panorama for Lake Mariut making it the most polluted one in Egypt. The Main Basin, the main object of this assessment, which covers an area of about 25 km², has been suffering from high levels of pollution. Currently, the main sources of pollution in this part of the Lake are caused by:

- (a) The West Treatment Plant Outfall, which discharges about 200,000–300,000 m³/day of settled sewage into the lake



North Delta Lakes, Egypt, Figure 14 Lake Manzalah, Egypt.

- (b) El Qallaa Drain Outfall, which discharge about 400,000 m³/day of agricultural wastewater and sewage into the lake after primary treatment (El Sharkawi, 1999; Kassim, 2005); in general, El Qallaa Drain is considered the major source of pollution in the lake (Samman et al., 1988)

In addition to these two sources of pollution, previously for a long period, Gheit El Enab Outfall was discharging about 25,000–35,000 m³/day of raw sewage and some industrial wastewater into the lake. Since the early 1990s, such quantity of wastewater has been directed to the West Treatment Plant (El Sharkawi, 1999). Also, about 25,000–30,000 m³/day of industrial wastewater used to be discharged into the Main Basin of the lake from the Moharam Bey Industrial Complex. Such industrial wastewater has high BOD, COD, oil, and suspended solids (Table 3).

Lake Mariut Physicochemical Descriptors (Water)

Moreover, the shores of Lake Mareotis embraced major production centers for different industries such as

glass, pottery, and wine, which contributed significantly to the economy of Alexandria and of Egypt as a whole. To date, however, Lake Mareotis has been a much underrated resource particularly with respect to its economic relation to Graeco-Roman Alexandria. Moreover, many archaeological sites located along the shores are endangered by modern urban development and various industrial and agricultural activities. Lake Mareotis, precursor of the present Maryut Lake, represented one of the most distinctive geomorphological features in the north-west coast of Egypt during the Holocene period. It was, and still is, quite unique compared to other lakes on the Egyptian north coast, which were formed as a result of the sea inundating the north coast of the Nile Delta. In antiquity, Lake Mareotis was formed solely by the Nile, which fed the lake through a network of canals that branched off the river's defunct Canopic Branch and approached the lake from the south and the east (Figure 19).

Moreover, it was connected to the sea at Alexandria through a navigable canal that debouched at the city's western harbor. Accordingly, besides being a freshwater

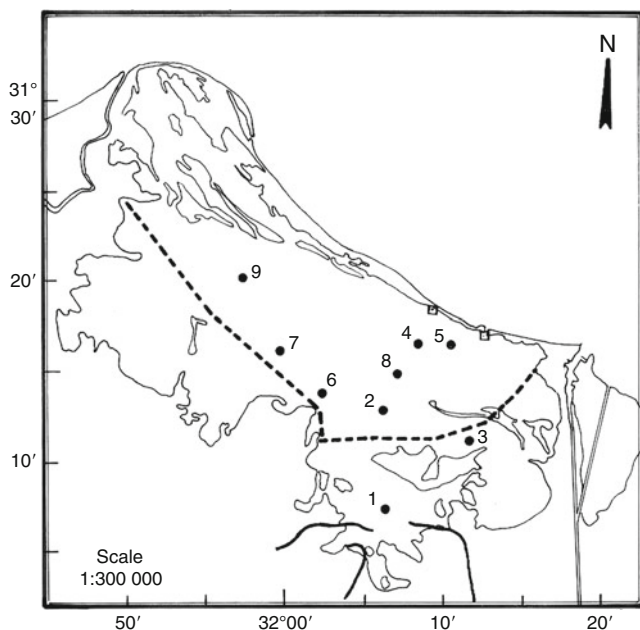
lake, Mareotis also gave access to the Nile and hence to the whole of Egypt.

Historical, archaeological, and geomorphological evidence indicate that Lake Mareotis consisted of two

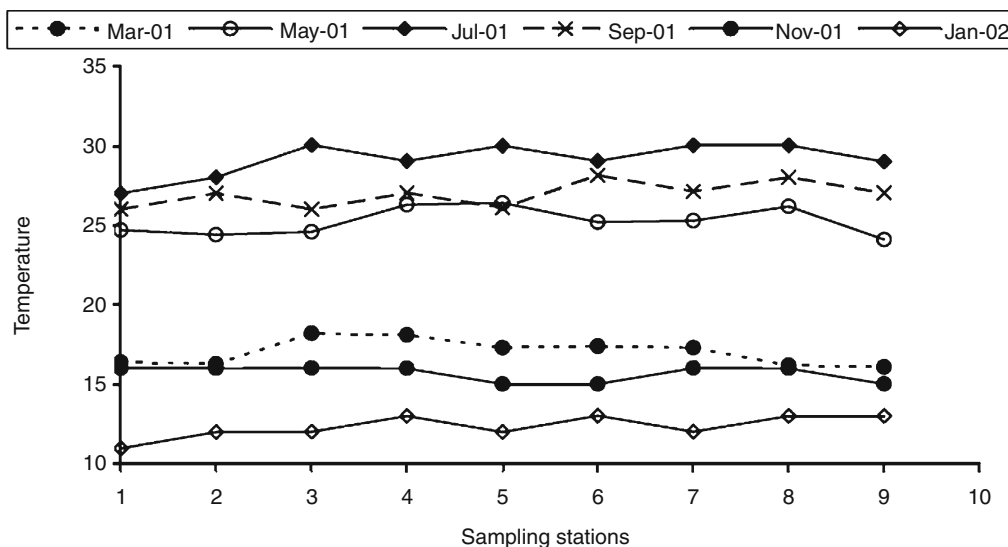
interlinked parts: the main basin of the lake, which extended for 40–50 km south of Alexandria, and a narrow arm, which was about 3 km wide and extended west of Alexandria for about 40 km. However, it is evident that Lake Mareotis has undergone dramatic changes during the past two millennia, which significantly affected its size and nature. During the fifth century A.D., the Canopic Branch started silting up and it became defunct by the twelfth century A.D. Accordingly, Lake Mareotis lost its connection to the Nile, and the once navigable freshwater lake became a closed lagoon with no constant supply of water. Due to increasing evaporation, the size of the lagoon decreased significantly and by the end of the eighteenth century Mareotis was almost dry, except in the rainy seasons. Lake Mareotis remained dry for almost 700 years until it was intentionally flooded with seawater twice in the early nineteenth century, as strategic actions, ending forever its life as a freshwater lake (Figure 20).

However, once again, Lake Mareotis started drying up due to increasing evaporation until most of its basin became dry arable land. It was not until the early twentieth century, when the major irrigation projects in the western Delta were established, that the depression started receiving agricultural runoff and irrigation water carried by a number of canals and drains, filling the depression and creating the present Maryut Lake.

At present, Maryut Lake is a body of shallow brackish water that occupies about 17% of its original size. It consists of two sections separated by a number of causeways and canals. The main body of the lake is nearly rectangular in shape, with its northern coast extending for about 20 km, while its eastern coast is about 12 km long. It has also been divided into many subbasins, which are used



North Delta Lakes, Egypt, Figure 15 Map of Lake Manzalah showing the main drains and location of the sampling stations. The main basins are: 1, Bahr Genka; 2, Bahr Lagan; 3, Bahr Bashtir; 4, Bahr Kassab; 5, Bahr El-Gainil; 6, Bahr Deshdee; 7, Bahr Abwat; 8, Bahr Kurumulls; 9, Bahr El-Zarka (After, Shakweer, 2005.)



North Delta Lakes, Egypt, Figure 16 Monthly variations of temperature at different stations of Lake Manzalah. (After, Shakweer, 2005.)

for industrial and agricultural purposes. Moreover, its shores are subject to continuous irrigation, drainage, and reclamation projects, which make it constantly changing and unstable. The second part of the lake takes the shape

North Delta Lakes, Egypt, Table 2 Average values of salinity and TDS during 1967, 2001 at El Gamil area of Lake Manzalah. (After, Shakweer, 2005.)

Month	Salinity during 1967 (Youssef, 1973)	Salinity during 1975 (El-Araby, 1990)	T D S 2001 present study
January	8.11	2.65	2.11
February	16.16	3.82	—
March	15.68	9.97	2.70
April	15.82	7.95	—
May	17.72	4.64	4.68
June	24.75	8.86	—
July	27.13	9.67	2.64
August	25.74	6.43	—
September	16.74	2.28	2.10
October	7.04	3.10	—
November	18.34	2.13	0.95
December	13.70	2.91	—
Average	17.24‰	5.37‰	2.53‰

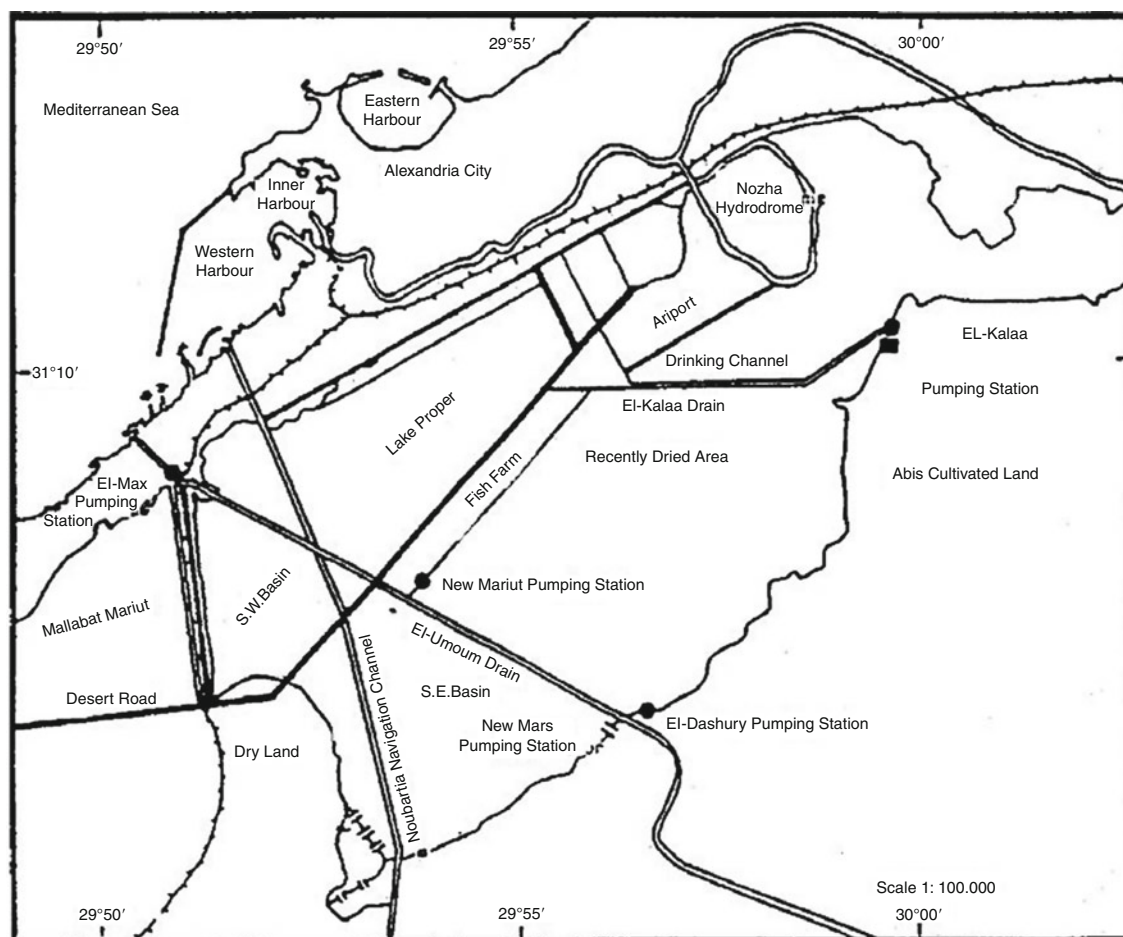
of a narrow arm that extends westward for about 40 km west of Alexandria. It is about 3 km wide and is delimited from the north and south by two coastal ridges. This western arm also contains an elongated Island which is about 4 km long and 500 m wide. Much evidence indicate that the western extremities of Lake Mareotis and its associated Island reflect the extant remains of the original lake that has not been subject to dramatic changes since antiquity. Since the lake receives its water from groundwater seepage, agriculture runoff, and rainfall, its water level fluctuates widely according to the seasons. In the rainy winter season, the water precipitates through the ground to raise the water level of the subbasin, while in the dry summer season, high rates of evaporation contribute to lowering the water level.

Idku Lake

Idku lagoon is the third largest coastal water body in the Nile delta. It is located in the northwestern part of the delta ($31^{\circ}12' - 31^{\circ}16'N / 30^{\circ}08' - 30^{\circ}18'E$) (Figure 21). The lagoon margin is essentially straight along its northern border; the eastern margin is bounded by Idku drain. The only connection of the lagoon with the Mediterranean Sea is the inlet Boughaz El Maadyah. The depth of the



North Delta Lakes, Egypt, Figure 17 Lake Maryut, Egypt.



North Delta Lakes, Egypt, Figure 18 Outline of Lake Mariut indicating the various basins, channels, drains, and pumping stations. (After, Mateo, 2009.)

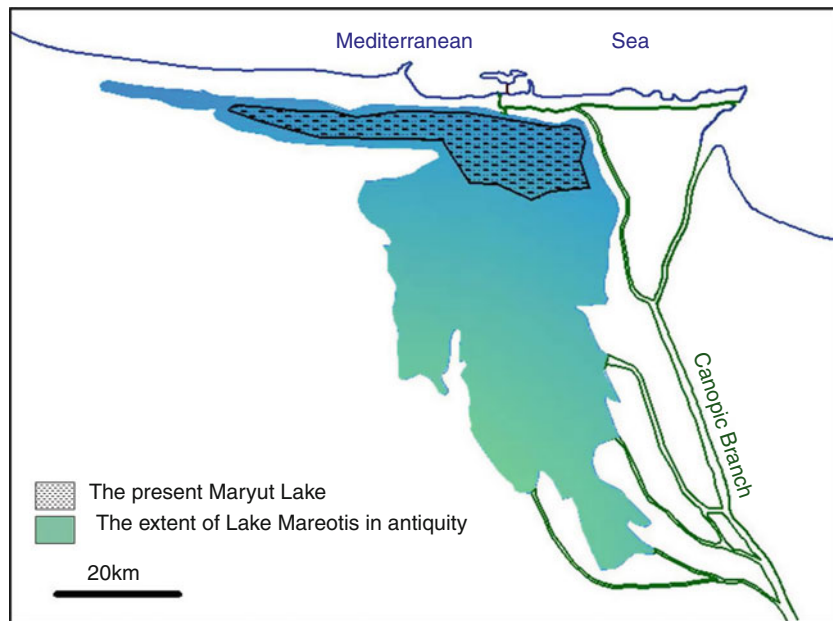
North Delta Lakes, Egypt, Table 3 Summary of the main descriptors measured in Lake Mariut. (After, Mateo, 2009.)

	Min	Max	Mean
Temperature (°C)	15.4	22.8	20.31
Depth (m)	0.4	1.5	0.90
Oxygen content (%)	0.8	131.4	52.1
Oxygen content (mg/l)	0.05	18.7	4.81
pH	6.79	8.7	7.50
Conductivity (mS)	0.85	20.1	5.03
Nutrients (mg/l)			
NH ₄	<0.1	118.7	14.96
NO ₃	<4	18.0	10.73
NO ₂	<0.02	1.44	0.51
PO ₄	<0.2	5.80	1.93
Heavy metals (mg/l)			
Cr	<0.02	0.3	0.05
Pb	0.7	4.60	3.31
Cu	<0.2	<0.2	<0.2

Idku lagoon ranges from 0.1 to 1.5 m. Lagoon waters are brackish, with freshwater discharging mainly from the Idku drain. This large drain, a branch of El Mahmudiya canal, collects drainage water from the Beheirah Province watershed (Saad, 1976).

Three main drains discharge into the lake, while Buoghaz El Maadyah provides a connection with the sea. The water in the lake is mainly fresh, but increases in salinity toward the Buoghaz and during the summer. Most of the lake margins are covered with dense growths of Typha and Phragmites, which cover about 50% of the lake's area. Saltmarshes, salinas, and high dunes, as well as some orchards, are found on the sandbar separating the lake from the Mediterranean. Lake Idku supports a fishery of moderate importance.

Lake Idku suffers from the same ailments that affect other delta wetlands: drainage and land-claim, pollution, disturbance, water bird catching, etc. Habitat loss through



North Delta Lakes, Egypt, Figure 19 The extent of Lake Mareotis in antiquity and at present. (Lake Mareotis Research Project, 2004.)



North Delta Lakes, Egypt, Figure 20 The topographic survey of the eastern end of the Mareotis Island. (Lake Mareotis Research Project, 2004.)



North Delta Lakes, Egypt, Figure 21 Lake Idku, Egypt.

land-claim is certainly the most serious of these threats. Lake Idku has been reduced to less than half its original size. Sewage and industrial wastes, discharged into the sea from the industrial complex along the Abu Qir coast (Figure 22) via El Tabia pumping station, west of El Maadyah, may at times enter the lagoon through the inlet at El Maadyah (Saad, 1978a). The wastes supplement those transported by Idku drain and other channels flowing into the lagoon.

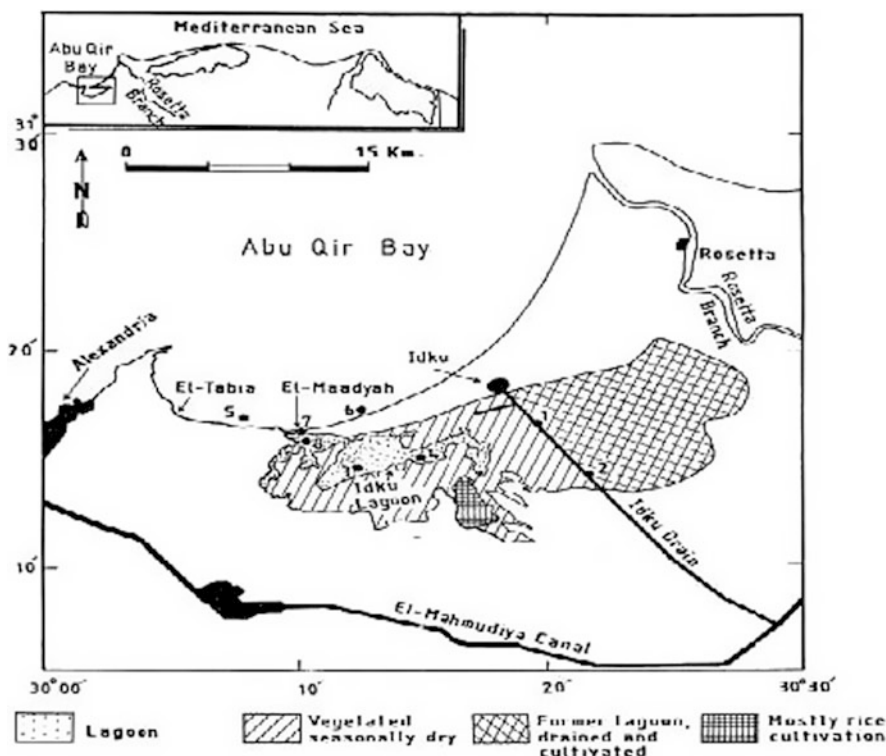
Numerous studies have considered the chemical and biological aspects of Idku lagoon (Saad and Ezzat, 1972; Saad, 1976, 1978a, b; Banoub, 1979, 1983). Idku lagoon is characterized by a marked variation in salinity (Saad, 1978a). This leads to its special feature of well-separated water masses that can often show concomitant phenomena in their biological and chemical characteristics. Domestic, agricultural, and industrial sewage contamination of the lagoon water is the most dangerous aspect since it results in high loads of allochthonous organic matter and nutrients, which enhance the growth of microbial mass as well as phytoplankton production. In addition, the introduced sewage may bring high numbers of microorganisms such as the pathogenic coliforms that might threaten aquatic plants and animals and also present a great hazard of public health.

General: This shallow brackish lake contains a number of islands and is situated 15 km SW of the mouth of the Rosetta branch of the Nile. It is 16 km long, has a maximum width of 10 km, and is separated from the sea by a narrow sand barrier. An extensive reed swamp at the eastern side has been partially reclaimed in recent years.

Hydrology and Water Quality: Water is received by drainage of the surrounding delta lands and exchange with the sea occurs through the Boughaz el Maadyah, with inflow from the sea occurring principally in winter. The lake is usually well oxygenated, and water temperatures range from 15°C to 29°C. Chloride ion concentrations range from 0.5 to 23 mg/l and total dissolved solids from 1,000 to 45,000 mg/l.

Flora and Fauna: The flora and fauna are much as described in the regional introduction. The lake supports *Ceratophyllum demersum* and dense mats of *Eichhornia crassipes*, with *Potamogeton crispus* and *Potamogeton pectinatus* in the most saline areas. It is eutrophic and highly productive. The eastern marshes are dominated by *Phragmites australis*. European animals such as *Lutra lutra* occur here.

Human Impact and Utilization: There is a flourishing fishery in which *Oreochromis* spp. account for 82% of the catch, *Anguilla anguilla* for 10% and *Mugil* spp. for 6%.



North Delta Lakes, Egypt, Figure 22 Location map of Lake Idku in northwestern Nile delta. (After, Saad, 1978a.)

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Cross-references

Arab Region, Lakes and Reservoirs
Circulation Processes in Lakes
Coastal Lagoons
Mixing in Lakes
Water Balance of Lakes
Water Exchange Between Littoral Zone and Open Lake Water

NUTRIENT BALANCE, LIGHT, AND PRIMARY PRODUCTION

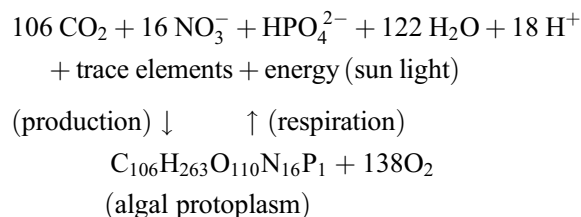
Thomas Hellström
Thellva HB, Dalarö, Sweden

Description

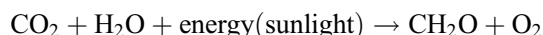
Primary production, which occurs in plants (from algae to trees), converts inorganic matter to organic matter. The driving force is sunlight. Organic matter contains energy. Prerequisites except sunlight are that nutrients and water are available. Main nutrients are phosphorus, nitrogen, and carbon dioxide.

Primary production is the input of organic matter and energy, which drives biology in all other trophic levels. Exceptions may be very small lakes in forests, where organic matter from forest litter can be an input of importance. Main primary production is normally due to growth

of microalgae. In shallow water, macrophytes may sometimes dominate the production. For algal growth, nutrients and energy are needed. Primary production produces energy-rich bonds as a result of photosynthesis. A simplified stoichiometry of the reaction looks like:



More simplified (less properly) the reaction is sometimes described as:



The production will go on until something limits. A number of nutrients and trace elements are needed. It is either sunlight or some nutrient or combination of nutrients that limits. During winter in those regions where there is a winter, sunlight is the limit. Otherwise most often phosphorus or nitrogen or both are limiting. As seen from the stoichiometry, nitrogen and phosphorus are needed in the molar ratio 16/1 (N/P). Algal production also causes an increase in oxygen and pH. Increase in pH does not occur if ammonium (NH_4^+) is the nitrogen source.

Respiration is the reaction backward. This is carried out by bacteria and other predators. Respiration also causes a release of nutrients, which can be reused. Some of the algal biomass will reach bottom sediments, and release of those nutrients (mainly phosphorus) cannot be reused immediately. Some will leach out from sediments and can be used later when it reaches productive upper layers, i.e., where sunlight is enough to drive photosynthesis.

When a system is running out of nitrogen (mainly nitrate, nitrite, and ammonium), a surplus of phosphorus will develop. Then cyanobacteria (also called blue-green algae) will start to grow. These organisms, which like bacteria are prokaryotic in cell structure, do not need nitrogen in the form of nitrate, nitrite, or ammonium for their growth. They can use dissolved nitrogen gas (N_2) directly. It is called N-fixation. The limit for cyanobacteria will be phosphorus. Through respiration (destruction), the biomass of cyanobacteria will feed the system with nitrogen.

Another limit factor can be short water detention time in the local system. This means that the algae are washed out before they could balance the system.

Sunlight during summer is more than enough near the surface. Sunlight can often limit photosynthesis at the surface because of too high intensity. Due to adsorption of sunlight intensity, it will decrease with depth and cause a maximum of production until it will fade out and stop photosynthesis at about 1% of the surface intensity. Adsorption of sunlight is mainly caused by particles including algae but will also decrease due to scattering

by water itself. When the algal biomass is high, the production can be strongly limited by self-shading.

Nutrients will increase due to various emissions and leaching from agricultural land. Nitrogen can also be added through atmospheric deposition. Phosphorus input through atmospheric deposition is normally very low. Phosphorus content is naturally the lowest in mountainous regions of crystalline morphology and increases in lowlands of sedimentary rock deposits.

In regions of lower phosphorus levels, nitrogen is in abundance, which also means that there are almost no cyanobacteria.

When the nutrient levels (i.e., phosphorus) are at high levels, this usually means high productivity and high abundance of organic matter. Organic matter is a driving force for denitrification. Denitrification means that some bacteria use oxygen in nitrate in their process of destruction of organic matter and leave nitrogen as nitrogen gas (N_2). Therefore, a lack of nitrogen compared to phosphorus can emerge. Therefore, presence of N-fixing cyanobacteria is more common in more eutrophicated waters.

Eutrophication means increased nutrient levels. The degree of eutrophication is classified after phosphorus

levels or after chlorophyll a. Chlorophyll is the pigment in algal cells, which carry out the photosynthesis. From low levels too high water are classified to be: oligotrophic, mesotrophic, eutrophic, and super eutrophic. There exist many classification limits between the different eutrophication groups.

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Cross-references

[Carbon Cycle in Lakes](#)
[Climate Change Effects on Lakes](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Health Aspects of Lakes and Reservoirs](#)
[Hydrodynamics of Very Shallow Lakes](#)
[Lake Restoration](#)
[Light and Primary Production in Lakes](#)
[Phosphor Exchange Sediment-Water](#)

O

OKEECHOBEE, LAKE, FLORIDA, USA

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Introduction

Lake Okeechobee is a large (1,730 km²), shallow (mean depth 2.7 m) subtropical lake located at the center of the Kissimmee-Okeechobee-Everglades watershed of southern Florida (Figure 1). The present-day lake contains three distinct ecological zones (Figure 2: Havens and Gawlik, 2005): a deeper *pelagic zone* underlain by mud sediments with waters high in nutrients and resuspended sediments, a shallower *nearshore zone* underlain by sand and peat sediments with varying water quality and coverage of submerged aquatic vegetation, and a *littoral zone* of sand and peat that is lower in nutrients and supports a diverse emergent wetland plant community that provides critical foraging and breeding habitat for much of the lake's fauna. Direct rainfall, most of which falls during the summer wet season, contributes over half of the water entering the lake, with much of the remainder coming from the lake's major tributary, the Kissimmee River, to the north. Due to its large surface area and warm climate, roughly two thirds of the lake's water losses are due to evapotranspiration, with water releases to estuaries on Florida's east and west coast, agricultural lands, and the Florida Everglades accounting for the remainder. The lake is managed as a multipurpose resource that provides significant economic and environmental benefits to the region. It plays a central role in regional flood control and water supply for more than seven million people (U. S. Census Bureau, 2010). The lake is used heavily by

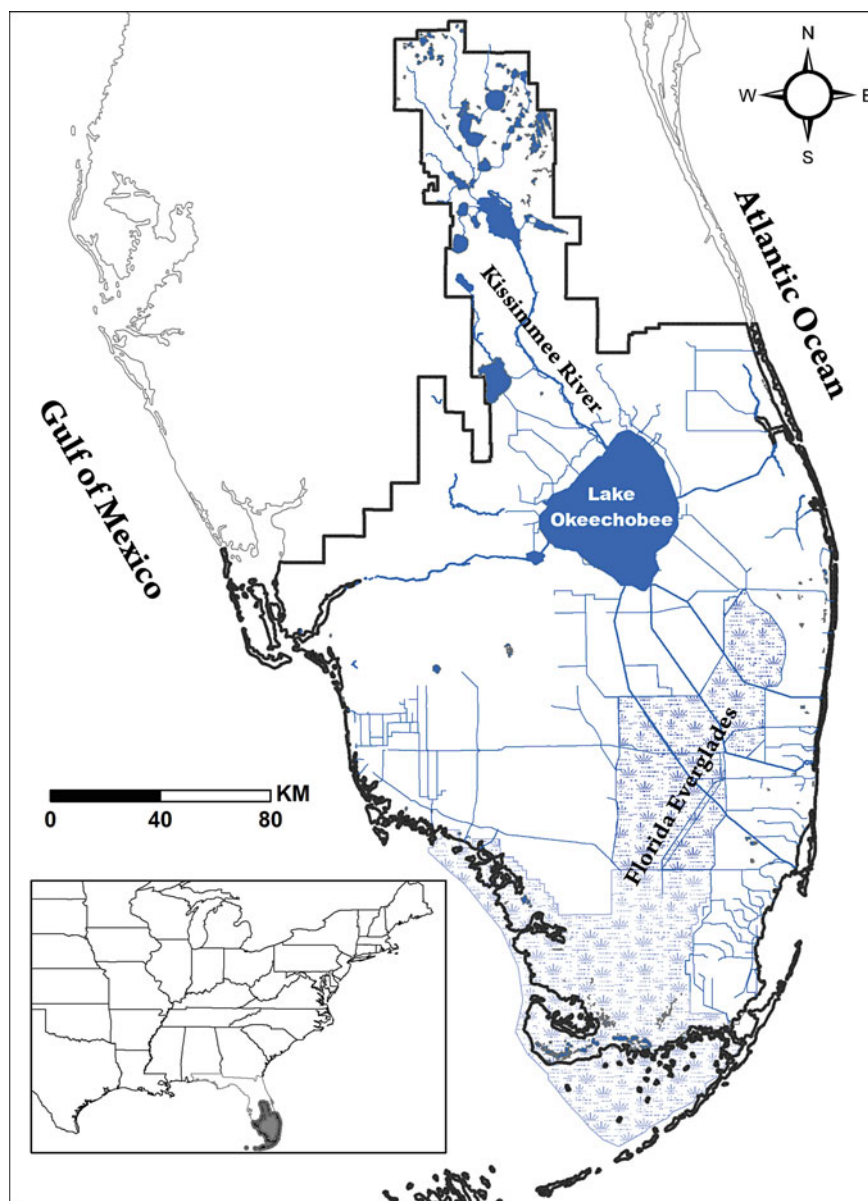
both resident and migratory water birds, including threatened and endangered species (Audubon of Florida, 2005), and contains an internationally recognized sports fishery that provides more than US \$17 million annually to the local economy (Bell, 2006).

Pre-settlement condition

The lake formed approximately 6,000 years BP in a large, shallow depression during a period of increasing rainfall and sea level rise following the last glaciation (Brooks, 1974). The depth of the lake increased in tandem with the accretion of deep peat soils in the sawgrass (*Cladium jamaicense*) wetlands of the Florida Everglades to the south, which formed a natural dam that had raised lake levels by 4–5 m by the late nineteenth century (Brooks, 1974). The Everglades also served as the sole natural outlet from the lake, which discharged large volumes of water seasonally as sheet flow across its broad southern shoreline. In addition to this direct connection to the Everglades, the pre-settlement lake was bordered on all other sides by a nearly continuous fringe of herbaceous and forested wetlands (Lodge, 2004).

Human modifications

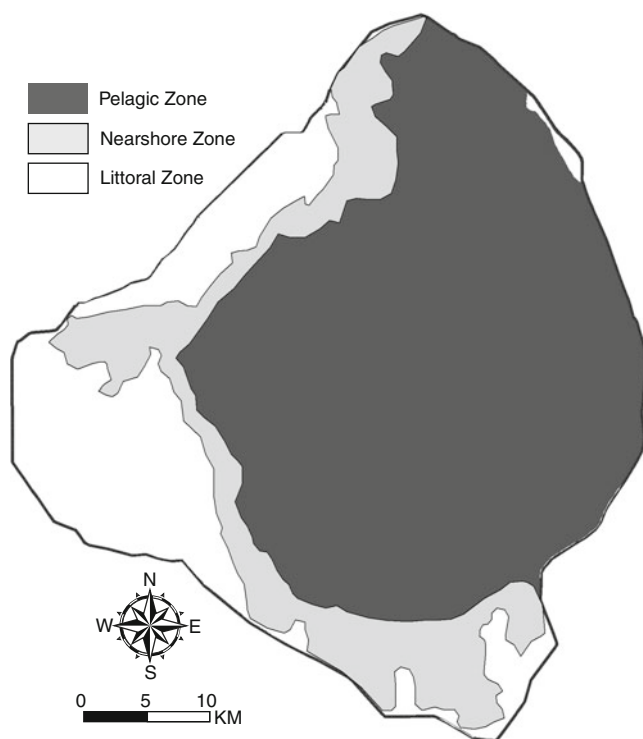
Lake Okeechobee has undergone substantial changes during the past century as a result of human development of the southern Florida peninsula (Blake, 1980). A series of regional drainage projects began in the 1880s to control Lake Okeechobee overflows to the Everglades with the goal of draining large areas of the Everglades peatland for settlement and agriculture. Over several decades, the State of Florida funded construction of a network of canals to divert lake water eastward and southward to the Atlantic Ocean and westward to the Gulf of Mexico, thereby lowering lake water levels and reducing the volume of overland flow to the Everglades. Deficiencies in



Okeechobee, Lake, Florida, USA, Figure 1 Location and current surface-water features of the Kissimmee-Okeechobee-Everglades watershed. Watershed boundary is shown by the thick black line. Major water bodies and man-made canals are shown in blue. The direction of water flow through the watershed is generally north to south and from Lake Okeechobee to the Atlantic and Gulf coasts.

this drainage plan were revealed when major hurricanes passing over the lake in 1926 and 1928 generated large lake storm surges that flooded newly settled land to the south and caused significant loss of property and life. This disaster prompted federal actions during the 1930s that included improvements to existing drainage canals and the construction of a 134-km long levee extending around much of the lake to prevent future damage from storm surges. While this levee successfully contained another

major hurricane surge in 1947, other aspects of the regional flood-control system proved inadequate to prevent widespread flooding of agricultural and urban areas across southern Florida. In 1948, the federal government authorized additional public works that created the present-day water management system. The lake's levee was increased in height and length so that it surrounded nearly the entire lake, and the conveyance capacity of drainage canals from the lake to Atlantic and Gulf



Okeechobee, Lake, Florida, USA, Figure 2 Major ecological zones of Lake Okeechobee.

coast estuaries was increased to improve flood protection. The major tributary to the lake, the Kissimmee River, was channelized, and a series of water-control structures were installed or upgraded to better manage flows into and out of the lake. Pumping stations installed in the levee along the south end of the lake allowed excess water in agricultural lands to the south to be discharged back to the lake, a reversal of the natural direction of water flow. This practice, referred to as “backpumping,” allowed for improved flood control during the wet season and additional storage of water for use during the dry season.

Current management issues

By the middle of the twentieth century, much of the watershed surrounding the lake had been converted to agricultural uses, including a thriving sugar cane and winter vegetable industry on the reclaimed peatlands to the south and extensive ranchlands, dairy farms, and citrus groves to the north and west. Runoff from these developed lands increased nutrient loads to the lake as a result of fertilization, manure production, and oxidation of drained organic wetland soils, resulting in rapid eutrophication of the lake (Joyner, 1974). The historically phosphorus (P)-limited lake switched to a nitrogen-limited state as in-lake total P concentrations increased from pre-settlement levels (estimated to have been between 20–40 $\mu\text{g L}^{-1}$) to

around 100 $\mu\text{g L}^{-1}$ by the early 1980s (James et al., 1995). Biological responses to this enrichment have included periodic lake-wide cyanobacterial blooms, a shift in the benthic invertebrate fauna toward nutrient tolerant forms, and the spread of nuisance vegetation in the littoral zone (Havens et al., 1996; Johnson et al., 2007). Eutrophication has also been associated with an increase in the depth and coverage of nutrient-rich mud sediments across the lake bottom. This trend is likely due both to an increase in biological production in the lake in response to nutrient enrichment and to the diked state of the modern lake, which prevents the natural flushing of accumulated sediments during hurricanes that periodically pass over the region. These sediments are estimated to contribute half of the annual P load to the lake (Moore et al., 1998; Fisher et al., 2005) and are easily resuspended under windy conditions, resulting in high turbidity and nutrient release (Jin et al., 2011).

The ecology of Lake Okeechobee is also susceptible to changes in water-level (lake stage) management. The lake is operated within a “regulation schedule,” which dictates lake stages where water is released and stored during different times of the year (USACE, 2008). When lake stages are near the lower end of this schedule, turbid, high-nutrient water tends to be restricted to the pelagic zone and water depths, and chemistry in the nearshore and littoral zones are conducive to the maintenance of submerged and emergent vegetation and associated fish and wildlife (James and Havens, 2005). Lake stages near the upper end of the schedule promote mixing of water among lake zones, resulting in poorer water quality and reduced plant growth. Peak inflow volumes to the lake exceed current outflow capacity, resulting in rapid increases in lake stage in response to heavy rainfall (Abtew and Iricanin, 2008). Consequently, the lake experiences prolonged periods of excessively high lake stages that damage aquatic vegetation and produce conditions unfavorable for wildlife foraging and breeding. The lake’s regulation schedule was increased by 0.6 m in 1978 to allow for additional water storage to support increased water demands from a rapidly growing human population. This change further exacerbated ecological impacts due to high lake stages (Lake Okeechobee Littoral Zone Technical Group, 1988) and increased the frequency of high-volume water releases to the coastal estuaries during wet periods to maintain the integrity of the lake’s dike, resulting in salinity and nutrient impacts in these downstream water bodies (Doering et al., 2002).

The lake’s littoral zone has experienced invasions of several exotic plant species that have displaced native wetland vegetation and reduced the suitability of this important habitat for fish and wildlife species. *Melaleuca* (*Melaleuca quinquivera*), a fast growing tree species from Australia, was planted inside the lake’s levee during the 1930s and 1940s to provide erosion control and quickly spread into the littoral zone. This species forms dense monocultures that displace other plant communities and provide poor wildlife habitat. Vigorous control efforts

have essentially eradicated this species from the lake. Another highly invasive, monoculture-forming species, torpedograss (*Panicum repens*), was introduced to the watershed in the 1940s as a forage crop for cattle and had spread across 6,700 ha (nearly 20%) of the littoral zone by 1996 (Hanlon and Brady, 2005). This species is being contained using a combination of management practices including prescribed burning and aerial spraying of herbicides, but complete eradication is unlikely. The lake also contains several species of exotic fish, many of which were unintentionally released from the aquarium and aquaculture trades. The effect of these introduced species on native fisheries and other ecological functions in the lake remains unclear. Many of these species are of tropical origin and may succumb to low water temperature experienced in southern Florida lakes and wetlands during unusually cold winters, thereby preventing sustained population increases (Shaffland et al., 2008).

Several measures have been taken to reduce environmental pressures on Lake Okeechobee caused by contemporary regional land use and water management. A plan was adopted in 1979 to eliminate the backpumping of nutrient-rich agricultural drainage water into the lake for water supply. In 1987, the Florida Department of Environmental Protection (FDEP) enacted regulations requiring the use of best-available technologies to reduce P loads to the lake from dairy farms to the north, which were determined to export more P on a per acre basis than any other land use in the watershed. A more comprehensive watershed plan for reversing eutrophication was initiated to achieve the Lake Okeechobee total maximum daily load of 140 metric tons (mt) per year established by FDEP in 2001. This plan requires implementation of agricultural best management practices and chemical treatment of farm runoff as well as the construction of large-scale treatment wetlands to remove additional P from the lake's tributaries (McCormick et al., 2010). Declines in in-lake P concentrations in response to watershed load reductions are expected to be slowed by continued internal P loading from the large quantity of mud sediment that has accumulated in the lake. A comprehensive study of sediment management options was initiated in 2002 and concluded that dredging this material would require 30 years and over US \$1 billion (in 2002) to complete (Blasland Bouck and Lee Inc., 2003) and would not appreciably reduce internal P loading due to the continued presence of residual sediments (James and Pollman, 2011). Chemical treatment of these sediments was determined to be a more effective option for reducing sediment P loading, but the treatment cost (US \$500 million in 2002), and the expected short-term duration of its effectiveness (8–15 years) also rendered this solution impractical (Blasland Bouck and Lee Inc., 2003). Therefore, emphasis continues to be placed on watershed P-load reductions with the recognition that the recovery of the lake will be a long-term process.

Improved stage management in Lake Okeechobee is dependent upon state and federal programs designed to restore some of the water storage and flow features that existed in the pre-settlement watershed. The goals of these multi-decadal efforts are to: (1) reduce reliance on Lake Okeechobee for water storage and flood control by constructing additional storage basins within the watershed and (2) allow for more natural high-volume lake discharges southward to the Everglades, thereby restoring the hydrology of this wetland and reducing the need for excessive lake releases to the estuaries (Steinman et al., 2002). Interim steps providing incremental improvements in environmental conditions in the lake and downstream water bodies include modifications to the lake's regulation schedule and the release of lake water to the estuaries in a manner that better mimics natural flood pulses (USACE, 2008). Cooperative programs between government agencies, private landowners, and other stakeholders have also been explored to increase water storage on private lands throughout the watershed to dampen the extreme fluctuations in water levels and flows that characterize the current developed watershed (Bohlen et al., 2009).

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Cross-references

[Everglades, Florida, USA](#)

ORIGIN OF LAKES AND THEIR PHYSICAL CHARACTERISTICS

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Definition

Catchment—The drainage basin which channels precipitation into a lake or single outflow.

Compartment—Any part of the environment or process which may conveniently be considered as a single entity. Used in developing mathematical models.

Compartment model—A model in which a series of compartments is used to represent the system of interest. Material can flow between the compartments. Differential or difference equations often are used to represent the rates of flow in the system.

Ecosystem—A community of organisms together with the environment they inhabit and with which they interact.

Epilimnion—The upper layer of lake water above the thermocline with a comparatively homogeneous temperature profile.

Hypolimnion—The layer of lake waters below the thermocline.

Morphometric—All the geometric characteristics relative to the shape of the basin (volume, surface, depth, etc.).

Residence time—The ratio of the volume of a water body to water discharge (corresponding to the theoretical time needed for a complete exchange of water).

Trophic level—The hierarchical level that an organism occupies in the food chain. The group of organisms that occupy the same level in the food chain.

Volume development—The ratio between the lake volume and the volume of a cone having the basis equal to the area of lake surface and the height equal to the maximum depth of the lake.

Classification schemes for lakes

The first classical work with a specific focus on the study of lake forms, describing their genesis and role in a broad limnological perspective, was *Limnological Methods* by Welch (1948). The source of morphometric data quantifying the size and form of lakes is the bathymetric map and such maps are today generally derived from echosounding, a technique that became more widely used after 1948. Most modern textbooks in limnology treat lake morphometry as if this were essentially a descriptive subject, but some attempts have been made to demonstrate why morphometry is of fundamental importance for the understanding of lake ecosystem functioning (see, e.g., Håkanson, 2004).

Lakes may be classified and categorized in many ways using different criteria. From a geological perspective,

lakes may be looked upon as causal objects on the face of the Earth. As all geomorphological features, lakes undergo different stages: creation, young age, maturity, old age, extinction. Lakes are generally created by drastic geological events, such as volcanism, tectonic activity, or glaciation. The relief of the basin is under constant alteration by exogenic forces, such as weathering, erosion, transport, and deposition. For example, all 227,000 lakes in Sweden (objects larger than 1 ha; see Table 1) have been influenced by the enormous form-creating power of the latest (but not last) glaciation. Eventually, all these lakes will be filled up and vanish, and the evident relationship between lake size and number of lakes in each size class will disappear. Hutchinson (1957) discussed all major lake types, their origin, morphometric characteristics, and distribution on Earth. He differentiated between 11 major lake types that were divided into 76 subtypes. The 11 major lake types are summarized in Table 2.

Lake morphometric characteristics are crucial for benthic organisms; zoobenthos, benthic algae, and macrophytes are functional groups of paramount importance in most lakes. The bottom sediments constitute the habitat for the benthic animals. Shallow lake areas may be regarded as a “pantry and a nursery” for the entire lake. It has been demonstrated that shallow areas can have a very high bioproduction capacity (many times higher than the most productive areas on land; see Rosenberg, 1985); all three functional groups of primary producers – phytoplankton, benthic algae, and macrophytes – are present in such areas (but not in open water areas in deep lakes), and where there is a high primary production, there is also a high secondary production of zooplankton, zoobenthos, and fish.

To analyze the relative importance of lake morphometry in relation to other factors that may influence fundamental lake variables, such as properties of the catchment area and climatological factors, it is important to realize that any lake variable will depend on factors causing seasonal variations within lakes and on factors causing variations in mean, median, or characteristic values among lakes. Lake morphometry will generally influence variations among lakes, but also many internal processes (sedimentation, resuspension, etc.). This means

that a given pollution load to a lake, for example, of nutrients and/or toxins, may cause very different effects in lakes of different morphometry. Effect-load-sensitivity analyses are of fundamental importance in lake management.

Echosounding and bathymetric map constructions have been discussed in several textbooks (see Håkanson, 2004) and will not be discussed here. All morphometric data, whether calculated using manual methods or digital approaches, such as Geographical Information Systems (GIS), emanate from a bathymetric map. There is a close relationship between the way in which the survey is carried out (the intensity and accuracy of the survey), the error in the bathymetric map, and the information value of the map. If there are no contour lines in the map, the information on the topographical features of the given lake is zero. The information value increases rapidly with the first number of contour lines, but if the number of contour lines becomes high enough, the gain in information becomes negligible, even if more contour lines are added.

Table 3 gives a classification of lake types based on trophic level (bioproduction level). Ultraoligotrophic (very low-productive) lakes are characterized by mean summer chlorophyll-a concentrations lower than 0.1 µg/l and by fish such as char and trout. Oligotrophic (low-productive) lakes have chlorophyll-a concentrations in the range from 0.1 to 1 µg/l and fish like trout and whitefish. One can note the characteristic level of total phosphorous overlap between the classes (see also OECD, 1982). The fish yield in mesotrophic lakes is about 0.9 g wet weight (ww) per m² per year, and by multiplication with lake area and 365 one can calculate an order-of-magnitude value on the annual fish production using this information. Eutrophic (high-productive) and hypertrophic (very high-productive) lakes have higher primary and secondary production.

Morphometric parameters and their role in lake studies

Starting from the bathymetric map, one can define a set of lake morphometric parameters describing lake size, form, and specific features and exemplify why and how these parameters are important in contexts related to the structure and function of lake ecosystems and in regulating the spread and effects of water pollutants.

Among the morphometric parameters, three main groups can be identified (see Figure 1):

- Size parameters: (1) different parameters in length units, such as maximum length, water depth, shoreline length, maximum depth, and maximum breadth; (2) parameters expressed in area units, such as 2D water surface area and 3D bottom area; and (3) parameters expressed in volume units, such as water volume and surface water volume (epilimnetic volume)
- Form parameters, based on size parameters, such as mean depth and shore development (= shoreline irregularity)

Origin of Lakes and Their Physical Characteristics,
Table 1 The number of lakes in Sweden arranged by size (Håkanson and Peters, 1995)

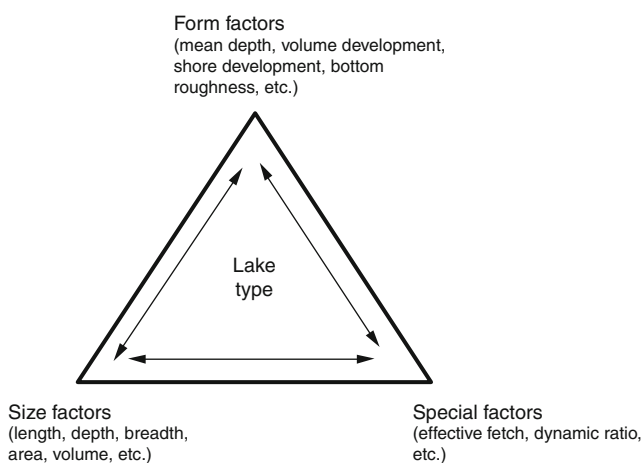
Area (1 km ² = 100 ha)	Number	Cumulative number
>1,000	3	3
100–1,000	19	22
10–100	362	384
1–10	3,987	4,371
0.1–1	19,374	23,745
0.01–0.1	59,500	83,245
0.001–0.01	144,000	227,000

Origin of Lakes and Their Physical Characteristics, Table 2 Major lake types on Earth according to Hutchinson (1957)

1.	Tectonic lakes, e.g., basins in faults (like Lake Bajkal and Lake Tanganyika)
2.	Volcanic lakes, e.g., maars, caldera lakes, and lakes formed by damming of lava flows
3.	Landslide lakes, e.g., lakes held by rockslides, mudflows, and scree
4.	Glacial lakes: A. lakes in direct contact with ice, e.g., lakes on or in ice and lakes dammed by ice B. Glacial rock basins, e.g., cirque lakes and fjord lakes C. Morainic and outwash lakes, e.g., lakes created by terminal, recessional, or lateral moraines D. Drift basins, e.g., kettle lakes and thermokarst lakes
5.	Solution lakes, e.g., lakes formed in caves by solution
6.	Fluvial lakes: A. Plunge-pool lakes B. Fluvial dams, e.g., strath lakes, lateral lakes, delta lakes, and meres C. Meander lakes, e.g., oxbow lakes and crescentic levee lakes
7.	Aeolian lakes, e.g., basins dammed by wind-blown sand and deflation basins
8.	Shoreline lakes, e.g., tombolo lakes and spit lakes
9.	Organic lakes, e.g., phytogenic dams and coral lakes
10.	Anthropogenic lakes, e.g., dams and excavations made by man
11.	Meteorite lakes, e.g., meteorite craters

Origin of Lakes and Their Physical Characteristics, Table 3 Trophic classification of lakes based on fixed steps (a factor of 10) of mean summer chlorophyll-a concentrations (Chl), typical ranges for total phosphorus concentrations (TP), phytoplankton primary production (PrimP in $\mu\text{g C/l-day}$ and $\text{g ww/m}^2\text{-year}$; a factor of 2 is used to calculate g C to g dw ; 5 to calculate g dw to g ww ; the effective depth of the photic zone is equal to the Secchi depth; and the duration of the growing season is set to 150 days), and dominating species of fish in the given classes. Also note that primary and secondary production in highly eutrophic lakes will be reduced by self-shading of algal cells (From Håkanson and Boulion, 2002)

Trophic level	Chl ($\mu\text{g/l}$)	Range TP ($\mu\text{g/l}$)	PrimP ($\mu\text{g C/l-day}$)	Characteristic PrimP range ($\text{g ww/m}^2\text{-year}$)	Characteristic fish yield ($\text{g ww/m}^2\text{-year}$)	Dominating fish species
Ultraoligotrophic	≤ 0.1	< 3	≤ 4.4	≤ 125	0.08	Char, trout
Oligotrophic	≤ 1	1–10	≤ 32	125–380	0.3	Trout, whitefish
Mesotrophic	≤ 10	5–40	≤ 270	380–1,400	0.9	Whitefish, perch
Eutrophic	≤ 100	20–400	$\leq 2,400$	1,400–6,400	3	Perch, roach
Hypertrophic	$\leq 1,000$	> 100	$> 2,400$	$> 6,400$	7	Roach, bream

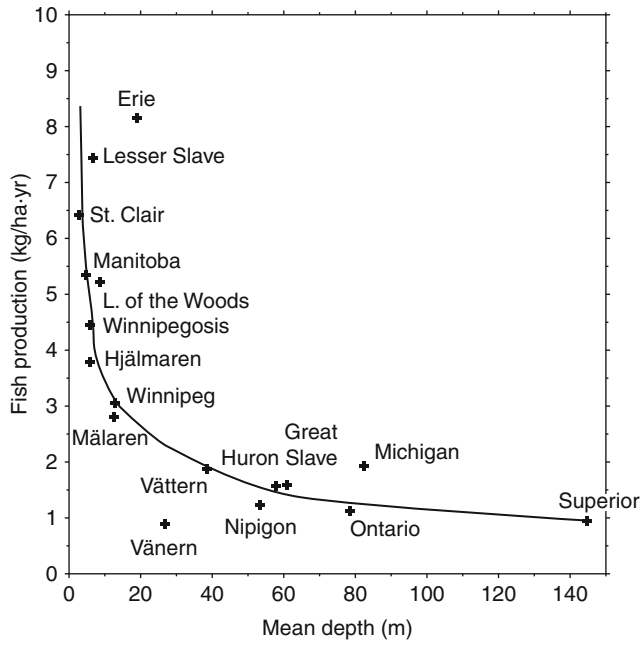
**Origin of Lakes and Their Physical Characteristics, Figure 1** The lake type may be expressed by morphometrical parameters describing different elements of size, form, and special features.

- Special parameters, like the dynamic ratio and the effective fetch.

The *maximum depth* ($D_{\max}$ in m) is the greatest known depth in the lake. The maximum depth is important in contexts of lake function, especially in defining the lake form factor (= volume development $V_d = 3 \cdot D_{\text{mv}}/D_{\max}$; see later).

Traditionally, the *mean depth* (D_{mv} in m) is defined by the ratio between the lake volume (V in m^3) and the lake area (A in m^2), or $D_{\text{mv}} = V/A$. The mean depth is a most informative and useful parameter in many contexts in limnology. This is exemplified here from the close relationship between mean depth and commercial fish production (Figure 2).

The *maximum length* ($L_{\max}$ in m) is defined by the line connecting the two most remote points on the shoreline. In regular basins, $L_{\max}$ is generally straight and concurs with the maximum effective length (L_{xel}). In irregular lakes, such as oxbow lakes, $L_{\max}$ is a curved line. It may not cross land, but it may cross islands. This rule means



Origin of Lakes and Their Physical Characteristics,
Figure 2 The relationship between commercial fish production and lake mean depth. (Data from Rawson, 1955 and Ahl, 1975.)

that $L_{\max}$ cannot always be given a definite value. It is primarily to be considered as a descriptive measure and has limited use in contexts on lake function.

The *direction of major axis* is defined by the general compass direction of the maximum length.

Traditionally, the *shoreline length* (L_0 , in m) may be estimated in different ways, for example, by a map measurer. To know the shoreline length is important to determine the shore development (L_d) and to calculate production and/or biomass of benthic algae and macrophytes.

The *mean breadth* (B_{mv} in km) is defined by the ratio between the lake area (A in km^2) and the maximum length ($L_{\max}$ in km), i.e., $B_{mv} = A/L_{\max}$.

Traditionally, *total lake area* (A_{tot} in m^2) is calculated by planimeter using a map in a given scale. If the scale factor (SF) is increased, small caps and bays will disappear on the map. This change will primarily affect determinations of shoreline length and not the area determination, since planimetry implies that negative errors (bays) are leveled out by positive errors (caps), provided that the planimetry is carried out on a map of reasonable scale, which is given by $\text{SF} \leq 5,500 \cdot \sqrt{A_{\text{tot}}}$. So, one can regard the area determination as rather independent of the map scale. The total area (A_{tot}) is an important parameter in many limnological contexts, but the *water surface area* (A in m^2) may be even more important. The water surface (A) is given by the difference in total area (A_{tot}) and the total area of islands, islets, and rocks (A_{ins}).

The lake *volume* is a fundamental variable needed to calculate, for example, lake concentrations of all types of substances ($C = M/V$) and the theoretical water retention time ($T = V/Q_{\text{mv}}$; Q_{mv} is the mean tributary water discharge) regulating the retention time of all substances in lakes.

The *relative depth* (D_{rel}) is defined by the ratio between the maximum depth (D_{max}) and the mean diameter of the lake (using the lake water area, A). Small and deep lakes have high D_{rel} values. The relative depth is often used as a measurement of the stability and stratification of water masses and to predict oxygen conditions in lakes.

Traditionally, the *shore development* (shoreline irregularity, L_d) is a dimensionless measure of the degree of shoreline irregularity and defined by:

$$L_d = \frac{L_0}{2} \cdot \sqrt{(\pi \cdot A_{\text{tot}})} \quad (1)$$

where L_0 is the shoreline length (in km) and A_{tot} is the total lake area (in km^2). The L_d value illustrates the relationship between the actual length of the shoreline and the length of the circumference of a circle with an area equal to the total lake area. A perfectly circular basin has a L_d value of 1. Irregular basins have higher L_d values. L_d values larger than 10 are rare, and one of the probably most irregular basins in the world, Lake Mälaren, Sweden, has an L_d value of 9.95. This lake is basically a big archipelago with many communication basins and bays. The shore development is a useful parameter in contexts of sediment sampling. The larger the lake and the more irregular the bottom and also the shoreline, the greater the variability in sediment characteristics and the greater the number of samples needed to obtain a representative mean value for the lake.

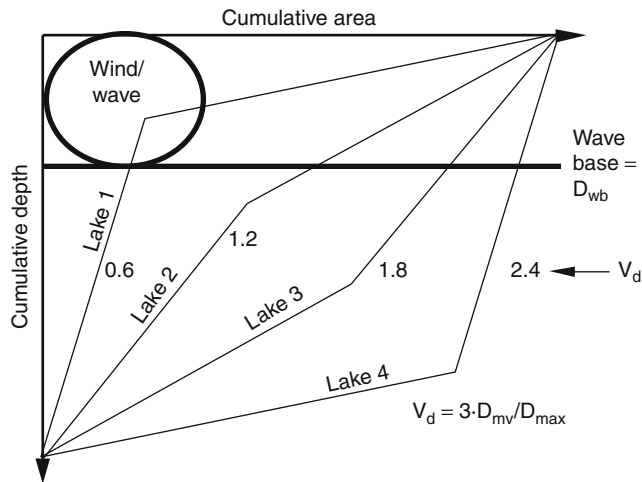
The *volume development* (or the *form factor*, V_d , dimensionless) is defined by the ratio between the water volume and the volume of a cone, with a base equal to the water surface area (A in km^2) and with a height equal to the maximum depth (D_{max} in m):

$$V_d = \frac{(A \cdot D_{\text{mv}} \cdot 0.001)}{(A \cdot D_{\text{max}} \cdot 0.001 \cdot 1/3)} = 3 \cdot \frac{D_{\text{mv}}}{D_{\text{max}}} \quad (2)$$

Where D_{mv} is the mean depth. The volume development describes the form of the lake and is also called the form factor. Table 4 and Figure 3 give the classification system for lake form based on the relative hypsographic curves and information on how V_d reflects lake form. One can note that lakes with very convex form (VCx) have small V_d values, and vice versa. This relationship is very important, for example, for internal processes. Shallow lakes have a large percentage of the bottom above the wave base, which is the water depth separating area where wind-induced waves can influence the sediments and above which there are resuspension events. Below the wave base, there is a continuous sedimentation of fine materials and no resuspension from surface waves.

Origin of Lakes and Their Physical Characteristics, Table 4 Classification system for defining the form of lake hypsographic curves and corresponding probabilities based on standard deviations (SD), class limits, and V_d values (Modified from Håkanson, 2004)

Lake form	Label	Probability (%)	Class limits (SD)	V_d
Very convex	VCx	6.5	f(-3.0) to f(-1.5)	0.05–0.33
Convex	Cx	24.2	f(-1.5) to f(-0.5)	0.33–0.67
Slightly convex	SCx	38.3	f(-0.5) to f(0.5)	0.67–1.00
Linear	L	24.2	f(0.5) to f(1.5)	1.00–1.33
Concave	C	6.5	f(1.5) to f(3.0)	1.33–2.00



Origin of Lakes and Their Physical Characteristics, Figure 3 Schematic illustration of relative hypsographic curves for four lakes with different volume development, $V_d = 0.6, 1.2, 1.8$, and 2.4 . Lakes with small V_d have large shallow areas subject to wind/wave-induced resuspension. Lakes with high V_d have greater volumes and steeper slopes, where slope-induced resuspension may occur.

The *dynamic ratio* (DR) is defined by the ratio between the square-root of the water surface area (in km^2 not in m^2), the $\sqrt{A}$ and the mean depth, D_{mv} (in m; $\text{DR} = \sqrt{A}/D_{mv}$). DR is a standard morphometric parameter in contexts of lake resuspension. For lakes $> 1 \text{ km}^2$, one can estimate the fraction of the lake bed where resuspension (a key component of internal loading in lakes) is likely to appear (see Håkanson and Jansson, 1983) from:

$$\text{ET} = 0.25 \cdot \text{DR} \cdot 41^{(0.061/\text{DR})} \quad (3)$$

Wind/wave-induced areas with dominating erosion and transportation areas for fine material (ET areas) are likely to dominate totally the bottom dynamic conditions in lakes with dynamic ratios higher than 4. Slope processes are known to dominate the bottom dynamic conditions on slopes greater than about 4–5%. Slope-induced ET areas are likely to dominate lakes with DR values lower

than 0.05. One can also expect that in all lakes there is a shallow shoreline zone where wind-induced waves will create ET areas, and it is likely that most lakes have at least 15% ET areas.

Some lakes on earth are extremely large and shallow, and one can assume that Lake Tchad, Africa, with an area of $24,000 \text{ km}^2$, a mean depth of 3.2 m and a dynamic ratio of 44.3, must be one of the most particular cases in this respect. It is exceptional for lakes to have DR values larger than 4 and smaller than 0.05.

The *wave base* (D_{wb} in m) is the depth separating transportation area (with resuspension) from accumulation areas (without resuspension). Functionally, this concept is fundamental in limnology since it distinguishes between surface water (epilimnion) and deep-water areas (hypolimnion), see Figure 4.

The *wave base* is related to the wave equation:

$$g \cdot \frac{H}{w^2} = 0.0026 \cdot \left(g \cdot \frac{L_{ef}}{w^2} \right)^{0.47} \quad (4)$$

where g is the acceleration due to gravity (m/s^2), H is the wave height (in m), w the wind speed (m/s), and L_{ef} the effective fetch (in m; see later).

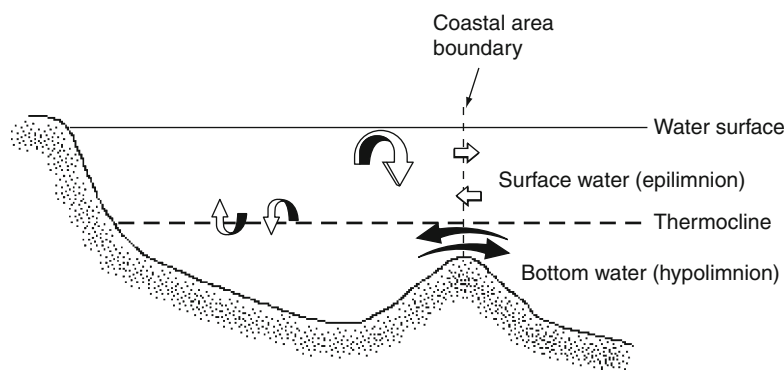
The depth of the wave base, D_{wb} , may also be derived from the ETA diagram. D_{wb} (in m) is then calculated from lake area (note that the area should be in km^2 and not in m^2 in Eq. 5), which is related to the effective fetch (the free water surface over which the winds influence the wave characteristics) and how winds and waves influences the bottom dynamic conditions:

$$D_{wb} = \frac{(45.7 \cdot \sqrt{A})}{(21.4 + \sqrt{A})} \quad (5)$$

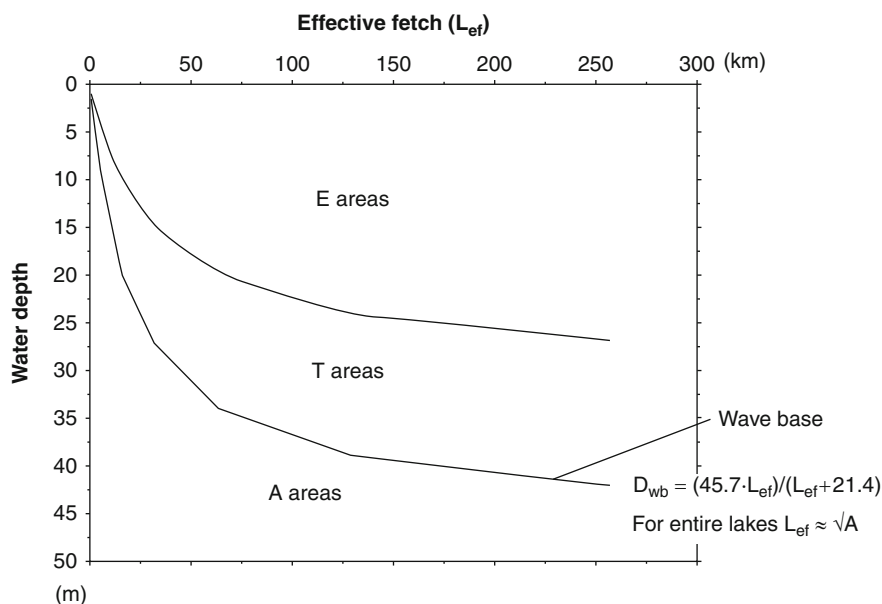
This approach gives one value of the depth of the wave base for any given lake.

The following processes influencing internal loading may be accounted for in an approach to predict the ET areas in lakes (see Håkanson and Jansson, 1983):

1. An energy factor related to the effective fetch and the wave base (see the ETA diagram in Figure 5)
2. A form factor related to the percentage of the lake bed above the wave base (see Figure 5)



Origin of Lakes and Their Physical Characteristics, Figure 4 Illustration of important concepts related to stratification, transport, and mixing in a coastal area in a large lake: surface water (epilimnion), deep water (hypolimnion), and thermocline.



Origin of Lakes and Their Physical Characteristics, Figure 5 The ETA diagram (Erosion-Transportation-Accumulation; for more information, see Håkanson and Jansson, 1983) illustrating the relationship between effective fetch, water depth, and bottom dynamic conditions. The wave base (D_{wb}) can be used as a general criterion to differentiate between surface water and deep water in lakes.

3. A lake slope factor related to the fact that slope-induced transportation (turbidity currents) may appear on bottoms inclining more than 4–5%

The *effective fetch* (L_{ef} in km) is often defined according to a method introduced by the Beach Erosion Board (1972). The effective fetch gives a more representative measure of how winds govern waves (wave length, wave height, etc.) than the effective length (L_{el}), since several wind directions are taken into account. The maximum effective fetch attains the highest values close to the shoreline and the minimum values in the central part of a basin. This relationship is important, for example, in

contexts of shore erosion and morphology, for bottom dynamic conditions (erosion-transportation-accumulation) and, hence, also for internal processes, mass-balance calculations, sediment sampling, and sediment pollution. It should be stressed that the theoretical wave base describes average conditions. During storm events, the wave base will be deeper and during calm periods at shallower depths. The wave base also varies spatially within the studied lake.

The hypsographic curve (see Figure 1.4) is obtained by putting depth as well as the cumulative area in percentage on the two axes. The relative hypsographic curve illustrates lake form and nothing but lake form.

The slope (Si) for an arbitrary site in a lake may be determined directly from the echogram, provided that the track follows the same direction as the major slope axis, which can be identified from the bathymetric map. The slope may be given in degrees or as a percentage of the height versus the length. The slope is an important morphometric parameter in contexts of lake sedimentology.

The insulosity (Ins in%), the percentage of the total lake area (A_{tot}) that is occupied by islands, islets, and rocks (Aist; see below for definitions), is estimated by dividing the area of all islands by the total area.

$$\text{Ins} = 100 \cdot \frac{A_{\text{ins}}}{A_{\text{tot}}} \quad (6)$$

The following classification may be used to distinguish islands, islets, and rocks (see Håkanson, 2004):

Area (km ²)	Name
<0.001	Rocks
0.01–0.01	Islets
0.01–1	Islands
>1	Large islands

Summary/conclusions

The way a lake looks and its morphometry (size and form elements) regulate the characteristics of a lake and the way a given lake functions. This section discusses an interpretational code which may be used to gain a better understanding of variations among lakes in fundamental lake ecosystem characteristics. The size and form of lakes regulate many general transport processes, such as sedimentation, resuspension, diffusion, mixing, burial, and outflow, which in turn regulate many abiotic state variables, such as concentrations of phosphorus, suspended particulate matter, pH and many water chemical variables, color, and water clarity, which in turn regulate primary production, which regulates secondary production, for

example, of zooplankton and fish. This understanding is the basis for a wider understanding of lake function and structure.

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Cross-references

[Classification of Lakes from Origin Processes](#)
[Lake Shore Nomenclature](#)
[Lakes as Archives of Earth History](#)
[Paleolimnology](#)
[Sweden's Great Lakes](#)

P

PALEOLAKES

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Introduction

All lakes are subject to a variety of extrinsic and intrinsic forcing variables that regulate the subsequent history of the lake. This includes age, climate, catchment, bedrock composition, tectonic and volcanic activity, vegetation, aquatic biota, and human activities. Strictly it is the history of change in these variables and the paleolimnological records of very old or ancient lakes that eventually lead us to the age of the lake.

Paleolimnological records found in three distinct types of archive

Water

Lake water itself and its contents have finite residence times, the time required for the average molecule of water to cycle through the system. In lakes with long residence time measured in say hundreds to thousands of years, the water itself may provide important paleolimnological clues to lake history.

Geomorphology

The geomorphology of the lake basin in its shoreline and shape characteristic features can persist for many thousands of years long after the lake has gone. In this respect, a lake basin evolution is a more useful concept than the static one of lake origin. It is therefore an essential element in the design of a paleolimnological study.

Sediments

Sediments provide the most durable feature since they may persist long after the lake itself, or its geomorphology ceased to exist.

Content archives in paleolimnological are the physical sedimentary inputs to the lake's record. These include terrigenous, chemical, and biogenic sediments; cosmogenic and volcanogenic particles; and fossils that originate outside the lake, like pollen, or in the lake, like fish, aerosols, and water-borne pollutants.

Formation and history of lakes

The formation and history of lakes has intrigued earth scientists for over a century; Hutchinson (1957) recognized 11 major categories of lake origins and since then advances have been made in understanding basin evolution using radiometric dating techniques, seismic stratigraphy, and lake drilling. The following lake classification (after Cohen, 2003) incorporates major elements of Hutchinson's scheme:

Basin closure	Temporal duration (years)
1. Glacial	10^4 – 10^5
2. Tectonic	10^5 – 10^7
3. Fluvial	$\leq 10^4$
4. Coastal	$\leq 10^4$
5. Volcanic	10^4 – 10^7
6. Wind	$\leq 10^4$
7. Solution	$\leq 10^4$ – 10^7
8. Landslide	$\leq 10^3$
9. Meteorite	10^5 – 10^7
10. Artificial	$\leq 10^3$

Paleolakes, Table 1 Ancient lakes (selection)

Lake name	Country	Age (million years)
Aral Sea	Kazakhstan, Uzbekistan	2–20
Baikal (Ozero Baykal)	Russian Federation	Greater than 20
Biwa (Biwa-ko)	Japan	2–20
Bosumtwi (Bosomtwe)	Ghana	1–2
Caspian Sea	Azerbaijan, Iran Kazakhstan, Russian Federation, Turkmenistan	2–20
Crater (2)	Canada	1–2
Eyre	Australia	Greater than 20
Hovsgol (Khuvsgul)	Mongolia	2–20
Issyk-Kul (Isyk-Kul)	Kyrgyzstan	Greater than 20
Lanao	Philippines	2–20
Malawi (Nyasa, Niassa)	Malawi, Mozambique Tanzania	2–20
Maracaibo	Venezuela	Greater than 20
Ohrid	Albania, Macedonia	2–20
Pingualuk	Canada	1–2
Prespa	Albania, Greece Macedonia	2–20
Taho	United States	1–20
Tanganyika	Burundi, Congo (Democratic Republic) Tanzania, Zambia	2–20
Titicaca (Lago Titicaca)	Bolivia, Peru	2–20
Vostok	Polar regions	1–20

Source: Lake Basin Management Initiative: LakeNet 2005

Table 1 gives a selection of ancient lakes of the order of 20^6 years.

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Cross-references

[Paleolimnology](#)

PALEOLIMNOLOGY

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Synonyms

Lakes as archives of earth history; Limnogeology

Definition

Paleolimnology is the study of lakes and lake sediments to reconstruct past climatic and environmental changes.

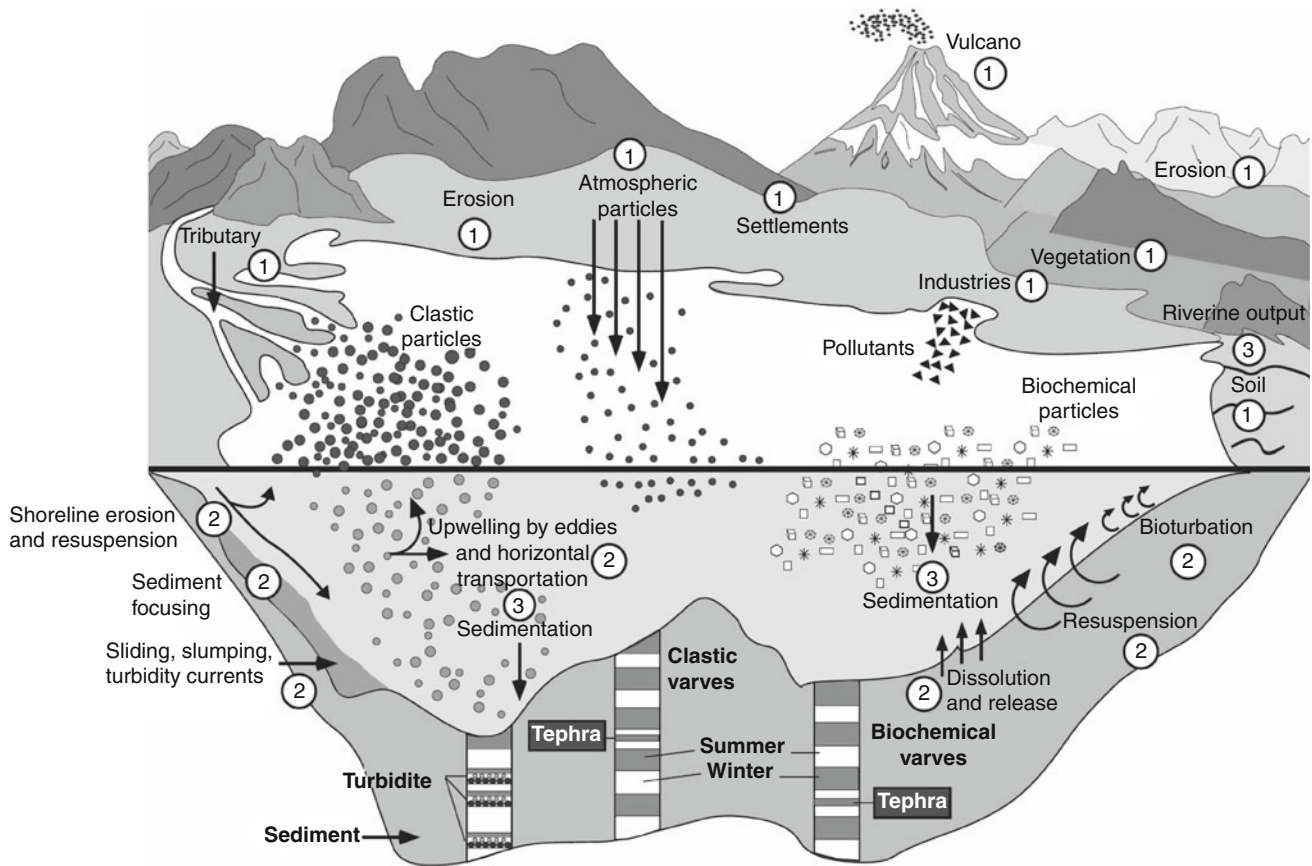
Introduction

Lakes have formed and vanished throughout Earth's history (see [Classification of Lakes from Origin Processes; Lakes on Earth, Different Types](#)), but their traces in the form of shorelines, sedimentary rocks, and sediments are often still preserved. The study of lake sediments and sedimentary rocks, to reconstruct environmental and climatic changes through time is called paleolimnology or limnogeology. No clear definition exists that would delimit these two terms, although paleolimnology is often used in the context of younger lake sediments (from present to ca. 2 million years ago), while limnogeology is more used to define the study of older lacustrine sediments and sedimentary rocks.

Paleolimnology as a science began with the study of lake development, i.e., with the observation that lakes change over time from oligotrophic (nutrient poor) to eutrophic (nutrient rich) conditions, as the lake fills with sediment, and the sediment–water interface becomes deoxygenated (Engstrom et al., 2000). The recognition of a “cultural” eutrophication later led to intensive studies of lake eutrophication and lake water acidification connected to human impact; and presently, paleolimnology forms an important tool for assessing natural reference conditions and restoration targets for lake ecosystems (Bennion et al., 2010; Bindler et al., 2010). Parallel with this development, lakes and their deposits have emerged as an important continental archive to reconstruct climatic and environmental changes on shorter (last 12,000 years) and longer time scales (last 2 million years). Ancient lakes (see [Paleolakes](#)) moreover are increasingly recognized as important evolutionary archives which allow assessing of the role of abiotic factors as driving forces for generating biodiversity (Rossiter and Kawanabe, 2000). Excellent overviews on paleolimnology and limnogeology are provided by O'Sullivan (2004); Cohen (2003); Last and Smol (2001a, b, c); Last et al. (2001); Gierlowski and Kelts (2000).

The study of lake sediments

Lake sediments are composed of autochthonous (formed in the lake itself) and/or allochthonous (transported into the lake by water and wind) material which are continuously deposited on the lake bottom (see [Lake Sediments; Sedimentation Processes in Lakes](#)) (Figure 1) (Bloesch, 2004). Anoxic bottom waters and absence of borrowing organisms in certain lakes allow the preservation of seasonal and annual layers (laminated or varved sediments), but in most lakes, sediments have become mixed and their original laminations have disappeared. Changes in the catchment and in the lake itself due to changes in environmental and/or climatic conditions and/or human impact are continuously registered in the sediments. Lake sediments are therefore sensitive recorders of local, regional, and even global changes which can be reconstructed using a variety of physical, chemical, and biological methods, so-called proxies (see [Lakes as Archives of Earth History](#)) (Last and Smol, 2001a, b, c; Last et al., 2001).



Paleolimnology, Figure 1 External and internal environmental factors influencing suspended sediments, sedimentation and sediment formation in a lake basin. 1 = sources of suspended particulate matter (SPM); 2 = transportation and transformation of SPM; 3 = removal of SPM. (From Bloesch, 2004, Figure 8.1.)

Methods used in paleolimnology include bathymetric and seismic surveys to determine lake depth and morphology, sediment thickness, distribution and unconformities, and past lake-level changes. Limnological data are collected to assess the present lake status, catchment land use and, nutrient supply, and to provide calibration data sets for down-core multi-proxy analyses. Sediment cores are obtained using a variety of different coring devices, ranging from gravity and freeze corers for the topmost and least consolidated sediments, to modified Russian corers (for shallow lakes) and piston corers (for deep lakes) to obtain undisturbed sediment sequences. Physical analyses of the sediments include lithostratigraphic descriptions to characterize the sediment type, structure and layer thickness, and mineralogy and mineral magnetic properties to assess the composition of the inorganic sediment fraction; these in turn provide information on, for example, sediment sources, transport mechanisms, depositional environments, and catchment erosion. Chemical sediment analyses comprise inorganic geochemistry which can give information regarding catchment erosion and lake status changes; organic geochemistry to assess, for example, lake productivity, aquatic/terrestrial inputs,

oxygen concentration, source of terrestrial material, biomarkers, and industrial pollution; and stable isotope chemistry to reconstruct changes in lake productivity, lake nutrient status, lipid biomarker sources, sources of lake waters, precipitation, lake hydrology, and lake water temperature. Biological analyses include, for example, pollen, spores, and plant phytoliths to reconstruct catchment, lake and/or regional vegetation history, and human impact; plant macrofossils to assess lake basin vegetation history; charcoal analysis to reconstruct catchment fire history; coleoptera to reconstruct ecosystem changes and temperatures; and limnic and terrestrial microfossils (diatoms, crysophyte cysts, ostracodes, cladocera, chironomids) to reconstruct changes in lake status (pH, salinity, nutrients, trophic state, temperature, precipitation). Chronological analyses (see *Age Determination of Lake Deposits*) provide an age frame for these reconstructions and enable correlations to other geological archives. Modern data sets (e.g., diatoms, chironomids, plant macrofossils, coleopteran, stable isotopes) and associated transfer functions are used to provide quantitative estimates of lake status changes, temperature, and precipitation.

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Cross-references

[Age Determination of Lake Deposits](#)
[Baikal, Lake](#)
[Caspian Sea](#)
[Dead Sea](#)
[Lakes as Archives of Earth History](#)
[Russian Lakes](#)
[Russian Lakes, Geographical Classification](#)
[Titicaca Lake](#)

PEIPSI LAKE IN ESTONIA/RUSSIA

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Introduction

Lake Peipsi is located south of the Gulf of Finland on the border between the Republic of Estonia and Russian Federation, being the largest international lake in Europe.

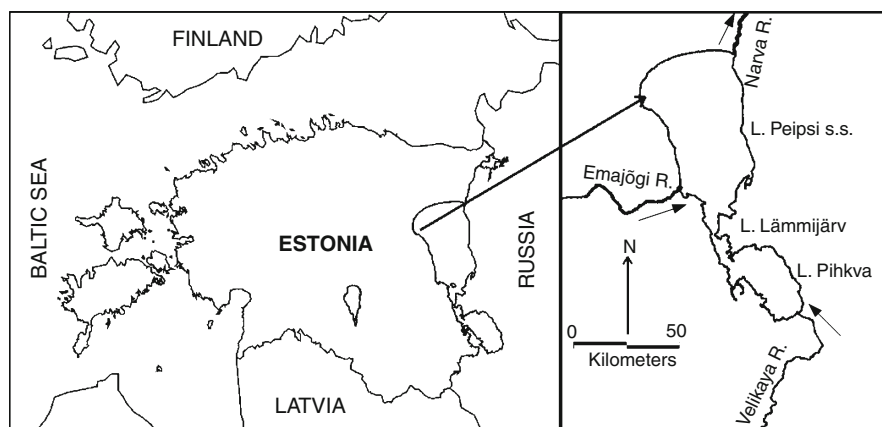
By its surface area (3,555 km²), Lake Peipsi is the fourth largest lake in Europe after Ladoga, Onego, and Vänern. Peipsi is a very old geographical name of Finno-Ugric origin in the northern part of the Eastern European Plain, but its etymology is uncertain (Jaani, 2001a). In old maps, the lake is depicted since the sixteenth century (Varep, 1995). At different times, the lake is known in slightly different forms: Peibes, Peibas, Peybass, Beibessee, Beibs, and Peips. Ancient name Peipus has persisted mainly in Germanic language literature. In recent literature and geographical maps, the lake appears under two names: Peipsi and Chudskoe (or Chudsko-Pskovskoe) of Russian origin. Slavic people called Finno-Ugric people living to west from Lake Peipsi “tšuds” (from “tšuzoi” meaning “foreign” in Russian).

Location

Lake Peipsi (Figure 1) is situated in the East European Plain between 57°51′–59°01′ N and 26°57′–28°10′ E at 30 m above the sea level. The surface area of Lake Peipsi is 3,555 km² (at the mean water level of 30 m a. s. l.), of which 1,570 km² (44%) belongs to Estonia and 1,985 km² (56%) to Russia (Jaani, 2001a). The lake is shallow with a mean depth of 7.1 m, a maximum depth of 15.3 m, and a volume of 25 km³. These characteristics depend greatly on the overall natural water level fluctuations of 3.04 m over the last 80 years, with an average annual range of 1.15 m (Jaani, 2001b). During the highest water level on May 12, 1924 (31.76 m a.s.l.), the surface area was estimated at 4,330 km² and the volume of water at 32.128 km³. At the lowest water level on November 7, 1994 (28.72 m a.s.l.), these values were 3,480 km² and 20.98 km³, respectively. Thus, the surface area of the lake may vary by 850 km² and the water volume by 11.15 km³.

Lake Peipsi, elongated in the north–south direction, is rather a lake system, consisting of three limnologically different parts (Figure 1). The northern part, Lake Peipsi s.s. (sensu stricto, Chudskoe in Russian), is the largest (2,611 km²) and deepest (average depth 8.3 m). The southernmost part, Lake Pihkva (Pskovskoe), measures 708 km² and is 3.8 m deep on average. The strait between them is Lake Lämmijärv (Teploe) (236 km²; mean depth 2.5 m). The names Lämmijärv and Teploe (“lämmi” in Estonian and “teploe” in Russian means “warm”) are hydrologically motivated because in spring and winter, its water is much warmer than in Lake Peipsi s.s. and Lake Pihkva.

The first inhabitants of the area were Stone Age hunters and fishermen. At the end of the third millennium B.C., cattle breeding and agriculture started to develop. Permanent agricultural settlements were founded in the first millennium A.D., at the end of which period, the Slavs reached the eastern coast of the lake. From the fifteenth to sixteenth centuries, fishing villages appeared on its coasts. At present, the sparsely distributed population (8–9 inhabitants per square kilometers) is mainly engaged in fishery and agriculture. Only 19% live in towns, and the number of habitants is decreasing.



Peipsi Lake in Estonia/Russia, Figure 1 Location of Lake Peipsi.

Islands and coastline

Lake Peipsi has 35 islands and islets with total area of 29 km², which forms 0.8% of the surface area of the lake. The islands are concentrated in the southern part of the lake. The biggest islands are Kolpino (11.1 km²), Piirissaar (7.5 km²), and Kamenka (4.0 km²). In Lake Pihkva, the Talabskij Archipelago consists of three small but high islands. Those were formed along the margin of the ice tongue which penetrated into Lake Pihkva basin during the Otepää Stade of the last glaciation. Island Piirissaar is a natural boundary between Lake Peipsi s.s. and Lake Lämmijärv. The threshold between the two lakes is cut by wide but shallow straits, which are located west and east of the Island Piirissaar and called the Estonian and Russian Gates, respectively. The 520-km coastline of Lake Peipsi is rather straight, without many disjunctures. In the southeastern corner of Lake Peipsi s.s., Raskopel Bay forms a small separate lake.

The catchment

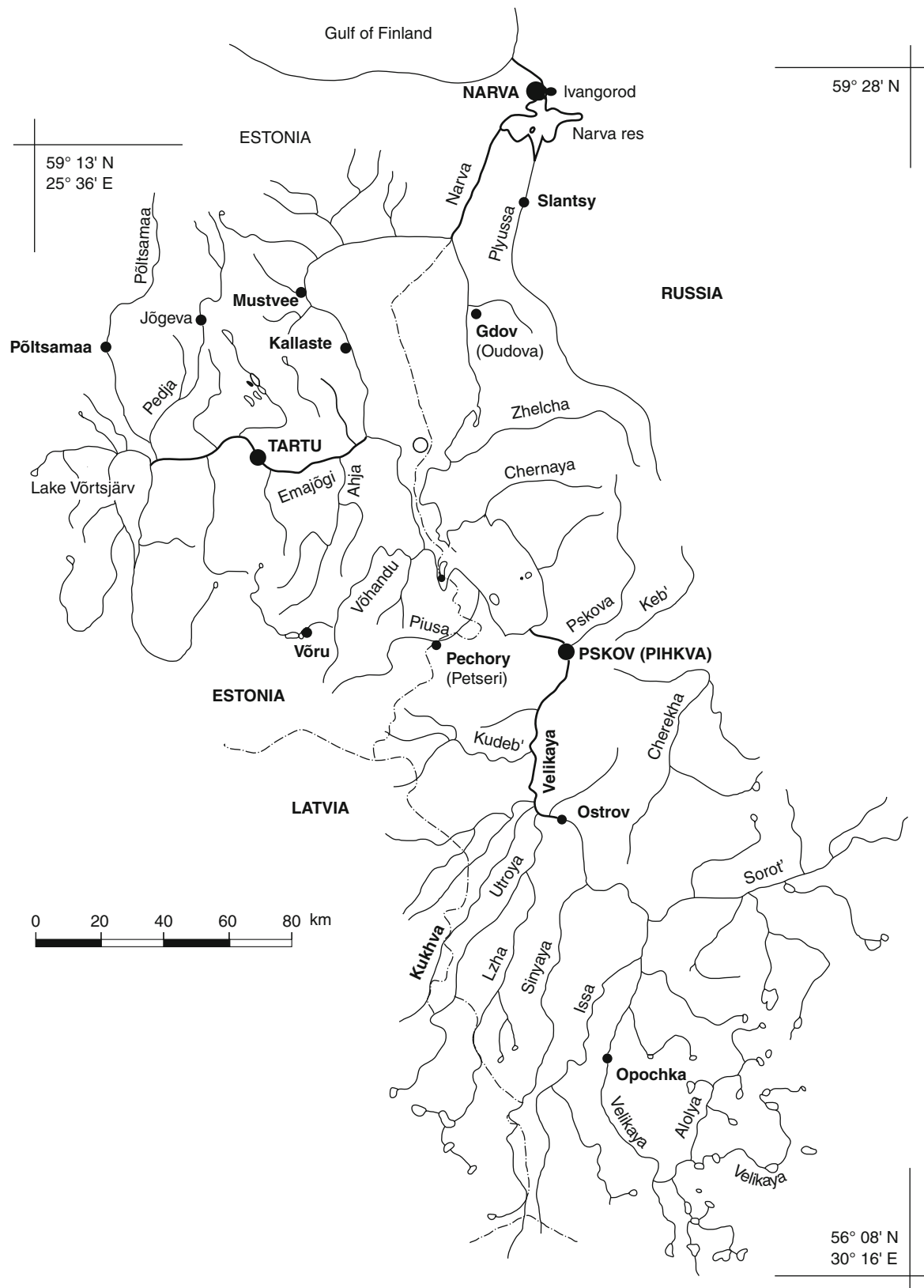
Lake Peipsi belongs to the Baltic Sea watershed and is linked with the Gulf of Finland via the River Narva (Figure 2). The submeridionally elongated catchment area of Lake Peipsi (47,800 km² including lake surface) extends from 59°13' to 56°08' N and from 25°36' to 30°16' E and is shared by Russia (27,917 km²), Estonia (16,323 km²), Latvia (3,560 km²), and, for a negligible part, by Belarus (Jaani, 2001a). The drainage basin is flat, with a highest point of 318 m above sea level. The lake catchment is mainly a gently undulating glaciolacustrine or till-covered plain. Forests and seminatural areas dominate in the lake drainage basin. Agricultural areas cover around 14% of the basin. The total population of the basin provides ca. 1,000,000 inhabitants.

The catchment area of L. Peipsi holds more than 4,500 lakes, the largest of which is a shallow, highly eutrophic Lake Võrtsjärv (270 km²). About 240 rivers and streams flow into Lake Peipsi. Catchment areas of the largest rivers are the following: the Velikaya (25,200 km²), the

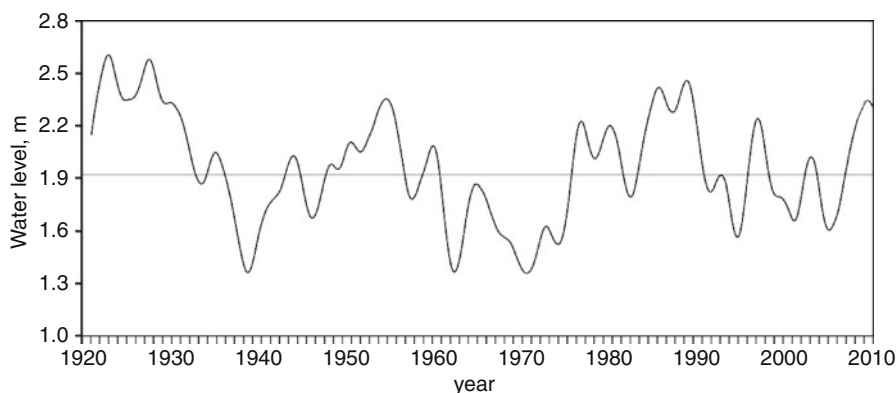
Emajõgi (9,745 km²), the Võhandu (1,423 km²), and the Zhelcha (1,220 km²) which account for 80% of the total inflow, thus controlling the water regime of the lake. The Velikaya River drains the largest portion of the Russian and Latvian parts of the basin and discharges into Lake Pihkva. Close to the river mouth is situated the major town of the area Pskov (191,961 inhabitants after World Gazetteer, 2010) which is the main point source of nutrients to Lake Pihkva. The Emajõgi River drains the majority of the Estonian part of the basin and discharges into Lake Peipsi s.s. The major town at the Emajõgi River is Tartu (102,455 inhabitants after World Gazetteer, 2010), which is situated about 50 km from the river mouth. The other bigger rivers include the Piusa (796 km²), the Rannapungerja (601 km²), and the Chernaya (530 km²). The outflowing River Narva (77 km long) is the second largest river after the River Neva flowing into the Gulf of Finland. The annual mean runoff through the River Narva is more than 12.5 km³, which makes about half of Lake Peipsi's water volume (25 km³) and about 3% of fresh water flowing to the Baltic Sea (Haberman et al., 2008). The average water retention time in Lake Peipsi is about 2 years. The water level is not regulated. A strong dependence of the water level on precipitation is characteristic of the hydrological regime of Lake Peipsi. Long-term variability of water level in Lake Peipsi has an expressive cyclic nature (Figure 3).

The geological setting

The thickness of the crust in the Lake Peipsi area increases gradually from about 45 to 50 km toward the south. The sedimentary cover is rather thin, ranging from 300 m in the north to 600 m in the south. Three sedimentary macrounits are recognized: Upper Vendian – Lower Ordovician siliciclastics, Middle Ordovician – Silurian carbonates, and Devonian, mainly siliciclastics (Müdel and Raukas, 1999). Most of Lake Peipsi belongs to the Devonian outcrop area. In the northern part of the lake, dolomitic marls with interlayers of dolostone, siltstone,



Peipsi Lake in Estonia/Russia, Figure 2 Catchment area of Lake Peipsi and the River Narva (after Jaani 2001a).



Peipsi Lake in Estonia/Russia, Figure 3 Mean annual water level in Lake Peipsi in 1920–2010.

and sandstone crop out. In the south, sandstones and siltstones with interbeds of claystones occur with dolomitic marls, dolostones, and limestones.

Peipsi is a natural lake and started about 13,000 radiocarbon (^{14}C) years ago as a big ice-dammed water basin. The Peipsi depression formed as a result of glacial erosion. The gently sloping bedrock surface is about 40 m above the sea level and is at its deepest (15–20 m b.s.l.) in the ancient valleys that were overdeepened by the glacier. The Quaternary cover is relatively thin, mostly less than 10 m. Several stadial till beds of the last glaciation have been found in the depression, differing in color and mineral composition (Raukas, 1978). Older tills have been identified only in the buried valleys. Two well-developed ice marginal belts are recorded by interrupted end moraines via Talabskij Islands in Lake Pihkva and Mehikoorma-Pnevo in Lake Lämmijärv.

Tectonic movements have exerted a strong influence on the formation of the lake. As the northern coast of the lake is lifting more rapidly, there is a gradual southward movement of the lake waters as a result of crustal tilting, which has led to the submergence of several Neolithic settlements in the vicinity of the lake. The chronicle of Pskov records that in 1458, a church was built on the Island of Ozolitsa. The remains of this church are now submerged beneath 0.4–2.5 m of water, and two small islets (Lezhnitsa and Stanok) are all that remains of the former island (Tyumina, 1966). During the last 10,000 years, the uplift in the northern part of the lake basin has been 10 m greater than in the southern portion of the lake (Miidel and Raukas, 1999).

A significant role in the sedimentation and resedimentation of bottom and coastal deposits is played by the lake ice. Almost every spring, ridges of pressure ice, up to 10 m high, are pushed forward against the shore, shaping the coast, redepositing older sediments, transporting huge boulders, and endangering the buildings.

Bottom sediments and shores

Bottom sediments are variegated. In the shallow coastal regions, sediments are relatively coarse-grained

(prevailing sands), whereas in sheltered areas (behind islets and in bays) and in the deep central part of the lake, fine-grained sediments (clayey silts and clays) dominate (Raukas, 1999). Usually, the sedimentary material is carried into the lake by the rivers and as a result of the erosion of the coast and lake bottom; it is then distributed under the influence of waves and streams according to bottom topography. The thickness of deposits is mainly 1–2 m and rarely over 10 m. The mineral and chemical composition of sand, silt, and clay fractions and the content of organic matter (up to 40% in Lake Peipsi s.s., 85% in Lämmijärv, and 35% in Lake Pihkva) as well as microelements is different in various parts of the lake. Fine-grained organic-rich sediments are very cohesive, playing the main role in the circulation of various inorganic and organic pollutants like nutrients and xenobiotics (Punning et al., 2009).

The abrupt cliffed shores (an abrasional escarpments in Devonian sandstone), scarp (an abrasional bluffs in sand, till, or peat), and erosional and flat erosional-accumulation shores are distinguished in Lake Peipsi (Tavast, 1999). The flat erosional-accumulation shores are divided into (1) till shore – an abrasional shore with a protective cover of boulders; (2) gravel shore – an accumulation shore with pebbles and gravelly sediments; (3) sandy shore – an accumulation sandy beach with a ridge of foredunes; (4) silty shore – an accumulation shore with silty-clayey sediments; and (5) artificial shore with manmade structures. During high stand of water, serious damages to the shores are registered. So in the 1920s, the people from Nina village were resettled. In 1987, at the northern coast, the sandy scarp retreated several meters, and near Alajõe, a 4-m-high new bluff formed into dunes. In 2010, serious damages were registered also on the western shore near Ranna.

Climate conditions

Lake Peipsi is situated in the northern region of the temperate zone with variable weather conditions. Summer temperatures can reach high extremes in the Peipsi area. Since 1924, the highest surface water temperature

(28.8°C) was measured in June 27, 1988. Water temperature commonly reaches its maximum in July, but it can happen from the beginning of June to the end of August. The lake belongs to polymictic type of lakes, where the complete mixture of water body takes place several times a year. Due to the lake's large surface area and relative shallowness, waves affect the bottom during the ice-free period. Therefore, thermal stratification is usually episodic and unstable and can be disturbed already by a moderate wind or undulation. Due to mixing, the water of the lake is usually rich in oxygen during the open water period. Lake Peipsi is, as a rule, covered with ice from December till April; however, the start dates of ice-cover and ice-off dates have been highly variable during recent years. Both the formation of ice and the melting process in Lake Peipsi normally take 2–3 weeks, but they can last up to a month. The first ice near the coast is usually formed in early November. In some years, the ice-cover period may last even to the beginning of May. Winter 2007/2008 was the warmest recorded during the whole period of measurements (142 years) in Estonia (Jaagus, 2008). According to measurements by the Estonian Institute of Hydrology and Meteorology, ice-cover destruction started already on January 19, 2008. Furthermore, the ice-cover thickness varies from year to year; the maximum thickness of ice can reach 75 cm and even more in some years. The near-bottom water frequently suffers from oxygen deficiency when the lake is ice-covered.

Lake type and limnetic variability

Lake Peipsi belongs to the shallow unstratified polymictic type of lakes with light water of medium hardness

(average 2.3 m Eq L⁻¹) located on mineral land. The considerable dimensions of the lake and relatively slow water exchange (the ratio of the volume to annual inflow) determine that the retention time for Lake Peipsi is about 2 years. The variability of limnetic parameters, typical for the large lakes, is characteristic for Lake Peipsi. The three lake parts have different morphometry, hydrology, trophic state, and humic content which provide a great variety of biotopes and support organisms with dissimilar ecological requirements. Most of the lake aquatory has lately been mesotrophic, which favors coexistence of the indicators of the meso- and eutrophic state as well as the species preferring a higher trophic state. Total species number of vascular plants and bryophytes is 140, algae are presented by 1,000 species, zooplankton contains about 300 species, macrozoobenthos has more than 400 species, and ichthyofauna includes 37 species.

At present, the lake as a whole is eutrophic, with a clear south-north gradient. The northern and deeper part, Lake Peipsi *s.s.*, is significantly poorer in nutrients than the southern, very shallow part, Lake Pihkva (Table 1).

Using the OECD (1982) classification system, the present-day conditions characterize Lake Peipsi *s.s.* as a eutrophic water body, while the trophic status of Lake Lämmijärv is close to hypertrophic and Lake Pihkva is a hypertrophic basin (Kangur and Möls, 2008). Differences in the water quality between the northern and southern parts of the lake (polarity) is caused, on the one hand, by the differences of natural environmental conditions, but on the other hand, it is determined by local human impact. The catchment area of Lake Pihkva is 2.5 times bigger than that of Lake Peipsi *s.s.* in relation to the surface area

Peipsi Lake in Estonia/Russia, Table 1 Selected morphometric, chemical, and phytoplankton characteristics of Lake Peipsi and its three parts (Lake Peipsi *s.s.*, Lake Lämmijärv, and Lake Pihkva). Water quality parameters are presented as geometric means, and 90% tolerance limits are given in brackets. These estimates correspond to the open water periods (Julian days 100–310 within each year) between 2006 and 2010 (After Kangur et al., 2011 submitted)

Characteristic	Lake Peipsi <i>s.s.</i>	Lake Lämmijärv	Lake Pihkva	Whole lake Peipsi
Surface area, km ²	2,611	236	708	3,555
Maximum depth, m	12.9	15.3	5.3	15.3
Mean depth, m	8.3	2.5	3.8	7.1
Water volume, km ³	21.79	0.6	2.68	25.07
TP, mg P m ⁻³	37.5 (17.1–82.0)	66.7 (31.9–139.6)	115.5 (53.1–250.8)	48.3 (16.7–140.2)
PO4-P, mg P m ⁻³	5.8 (1.1–32.7)	10.5 (2.0–54.9)	26.5 (7.0–101.0)	8.3 (1.2–51.5)
TN, mg N m ⁻³	703 (417–1,188)	896 (573–1,401)	1,143 (829–1,577)	784 (439–1,400)
^a DIN, mg N m ⁻³	122 (31–470)	127 (30–532)	96 (48–194)	121 (32–458)
Chlorophyll <i>a</i> content, mg m ⁻³	17.9 (5.9–53.9)	33.3 (13.6–81)	62.7 (26.2–149.6)	23.7 (6.4–88)
Secchi depth, m	1.8 (1.0–3.2)	0.95 (0.6–1.5)	0.7 (0.4–1.0)	1.4 (0.5–3.4)
OECD (1982) classification	Eutrophic	Eutrophic/hypertrophic	Hypertrophic	Eutrophic

^aDIN is the sum of ammonium ion, nitrate ion, and nitrite ion concentrations

and 5 times bigger in relation to the volume of the lake. It means that natural nutrient load to Lake Pihkva is significantly higher than in Lake Peipsi *s.s.* Although Lake Peipsi has been a center of human activities for centuries, the nonuniform anthropogenic impact to the different lake parts has especially intensified during the last decades. The loss of resilience and stability of Lake Peipsi ecosystem poses a risk to biodiversity and ecosystem functioning, as well as to human livelihoods dependent on water ecosystem services.

Multiple stressors

The wide diversity of coexisting human impact (e.g., eutrophication, pollution, overexploitation, introduction of nonindigenous species) and natural (e.g., extreme weather events, fluctuations in water level and temperature, changes in ice conditions and water retention time) stressors are affecting the Lake Peipsi ecosystem dynamics. Multiple stressors are causally linked to socioeconomic and natural processes in the large catchment area of the lake located in different landscapes.

Eutrophication

As in many shallow lakes, eutrophication (nutrient enrichment from human activity) remains the most serious environmental problem for Lake Peipsi triggering changes in the whole ecosystem. Lake Peipsi receives pollution mainly through river water and precipitation directly into the lake. Riverine transport is the most important pathway for input of nutrients from both point and nonpoint sources to Lake Peipsi (Loigu et al., 2008). The majority of phosphorus (P) and nitrogen (N) compounds are carried into the lake by the Velikaya River in the Russian Federation and by Estonian Emajõgi River. These two rivers account for 74% of the total nitrogen load and of total phosphorus load in Lake Peipsi (Loigu et al., 2008). The Velikaya River alone accounted for approximately 52% and 41% of the total phosphorus and nitrogen load, respectively. According to assessments for 2001–2005, Lake Peipsi received 8,324 t N year⁻¹ and 96.5 t P year⁻¹ and 8,532 t N year⁻¹ and 171 t P year⁻¹ from Estonian and Russian parts of the catchment, respectively (Loigu et al., 2008). According to estimates by Buhvestova et al. (2011), the average annual load of nutrients discharged into Lake Peipsi *s.s.* by major Estonian rivers during the period 1992–2007 comprised 5,600 t of N and 179 t of P. However, the major part of the loading from the south reaches Lake Peipsi *s.s.* through Lake Lämmijärv. According to calculations of Rumyantsev et al. (2005), average annual load of P to Lake Peipsi *s.s.* both through the rivers of the Russian part of the catchment and the waterflow from Lake Pihkva during the time span 1992–2003 comprised 280 t. Thus, the value significantly exceeded our calculated average annual Estonian riverine load for the period 1992–2007 (179 t of phosphorus). The average annual area-specific Estonian riverine export of TP to lake Peipsi *s.s.* was estimated at 0.16 kg P ha⁻¹ year⁻¹, while the value of TN was 5.1 kg N ha⁻¹ year⁻¹ (Buhvestova et al.,

2011). However, the estimates of external load to Lake Peipsi from the Russian part of the catchment area have been scarce. Nutrient concentrations in rivers discharging into Lake Peipsi are probably still influenced by nutrient stores from the period of intensive fertilization. The loading of N into Lake Peipsi *s.s.* from the Estonian catchment decreased substantially from the period of intensive agricultural activity in the 1980s to the present time, whereas the loading of P decreased much less. Especially the accumulation of phosphorous in soils will influence P losses on long-term, and the leaching of nutrients can continue for decades after reduced fertilization because of the soil's capacity to retain nutrients.

The increasing difference in total phosphorus (TP) concentrations between the northern and southern parts of the lake (polarity) clearly shows that the input of P from the south is increasing (Kangur and Möls, 2008). This can be considered as an indication of lake eutrophication. In the case of Lake Pihkva, a critical threshold level of P seems to have been exceeded and the lake is “full” of P (Kangur and Möls, 2008). Evidently, Lake Pihkva is losing its resilience. Also, Nõges et al. (2007) supposed the growth of phosphorus loading from the Russian subcatchment in the period 1992–2002, in comparison with loading of 1980s. In contrast, the polarity total nitrogen (TN) concentration in lake water remained relatively stable over the years and can be related to differences in natural conditions between different parts of the lake. Moreover, it refers to the resilience of the lake to year-to-year changes in riverine loads of nutrients. This might be due to in-lake processes: N₂ fixation and denitrification. Moreover, owing to lake's shallowness and relatively long water residence time (about 2 years), the natural processes, especially fluctuations of water level and temperature, can have influenced the lake water quality. As there is a big storage of phosphorus in the sediments of Lake Peipsi (Punning and Kapanen, 2009), lower values of water level in combination with higher summer temperatures could have enhanced the internal nutrient loading, which was followed by increase in TP concentration in lake water. It is especially evident in shallower Lake Pihkva, which is characterized by greater temporal variation of water quality, while the larger, deeper northern part, Lake Peipsi *s.s.*, is more resilient to natural environmental changes. Thus, in-lake TP concentrations can be more sensitive to natural changes in water level and temperature than to year-to-year changes in riverine nutrient loads.

A considerable effort has been invested to reduce external nutrient loads, primarily of P loading to Lake Peipsi. Since 1998, wastewaters of Tartu have been purified chemically, and the efficiency of P removal has been about 85–90%. Wastewaters from Pskov are purified only biologically, and most of phosphorus is not removed yet (Loigu et al., 2008). As Peipsi is situated on the border of the EU, state and regional, economical, and political interests are affecting the water management planning. The transboundary conditions complicate the

implementation of policies that might prevent or mitigate environmental damage in the Peipsi region.

The limnological time series data (from the 1950s to 2010) indicate deterioration of lake water quality and adverse changes in the whole ecosystem of Lake Peipsi. A deterioration of the lake's ecological status is indicated by massive blooms of cyanobacteria, oxygen deficiency, and cyanotoxins in water, shifts in species composition and dynamics of phytoplankton, expansion of reeds and loss of small-sized amphibious plant communities, mass development of epiphyton, accumulation of organic sediments, drastic decrease of zooplankton abundance, changes in the structure of fish community, silting of spawning areas of fish, and summer fish kills. Eutrophication has been the most rapid in the southern parts of the lake: in Lake Pihkva, which is directly affected by pollution coming from Velikaya River in Russia. Doubled TP, dissolved inorganic phosphorus (PO₄-P), silica (Si) and chlorophyll-*a* (Chl *a*) contents, increased total alkalinity (HCO₃⁻) and pH, as well as decline in water transparency and oxygenation conditions during the last decades, indicate an increase in the trophic level of Lake Pihkva (Kangur et al., 2007b).

Macrophytes

Among the rich flora containing about 150 macrophyte species, dominating have always been *Potamogeton perfoliatus* L. among the submergents and *Phragmites australis* (Cav.) Trin. ex Steud. among the emergents (Mäemets et al., 2010). Some species of mesotrophic stage became extinct in the 1980s (*Isoetes echinospora* Durieu and *Subularia aquatica* L.) or are suppressed (*Alisma gramineum* Lej., *Potamogeton filiformis* Pers., etc.) (Mäemets and Freiberg, 2004). In Lake Peipsi, the expansion of reeds has been the most evident result of eutrophication during the last 40 years. Increase of reeds is especially remarkable in Lake Peipsi s.s. where mesotrophic status is replaced by eutrophic. Since the end of the 1960s, the average biomass of reed per square meter has increased more than 70 times in the northern part of the lake (Mäemets, 2005). The success of reeds on Lake Peipsi has three main causes: (1) high nutrient loading, especially in the 1970s and 1980s, (2) low-water period at the end of the 1960s and beginning of the 1970s, and (3) diminishing or cessation of grazing (Mäemets and Freiberg, 2004). Expansion of reeds causes decrease of floristical diversity and increase of uniformity of lake parts. The expanding reed belt provides favorable growth conditions for the wind-sensitive shade-tolerant species of hypertrophic waters (*Spirodela polyrrhiza* Schleid., *Ceratophyllum demersum* L.) (Mäemets, 2005). Tall reed shoots shadow the habitats of the light-demanding small-sized species, and slowly decomposing litter covers large areas. Recent depth limit of reeds reaches mostly 1 m. Their expansion seems to be quite analogous to the result of fertilization experiments on grasslands where addition of nutrients favored the decrease in species number and prevalence of large-sized graminaceous species (cit.

Mäemets et al., 2010). Eutrophication has expanded northward along the longitudinal axis of the lake. So the reeds have occupied the northwestern shore of the lake during the 1980s and have appeared on the northern dyne shore during the last decade. Their establishment there is hindered by bottom conditions (moving sand) and changing water level. However, on the more flatten and sheltered shore stretches permanent stands exist now also in the northern shore. The growth rate of reed stands in eutrophic conditions may exceed 1 m per year.

In parallel with the direction of the eutrophication northward, expansion of nutrient-demanding species toward the northern part has taken place already in 1970s, when there appeared *Zannichellia palustris* L., *Elodea canadensis* Michx., *Ranunculus circinatus* Sibth., *Ceratophyllum demersum* L., *Lemna trisulca* L., *Spirodela polyrrhiza* (L.) Schleid., and *Potamogeton pusillus* L.

The richest flora of Lake Peipsi was characteristic for the period of the coexistence of nutrient-demanding and nutrient-sensitive species in 1970–1980. Macrophyte species richness has decreased in parallel with lake eutrophication. Comparing the frequency of the 67 species in the stations around the whole lake in 1970–1980 and in 1997–2007, a statistically significant decline occurred in the case of 20 taxa, among them frequency decreased twofold for 15 species. The most obvious reason for these changes is the occupation of the littoral by reeds (Mäemets et al., 2010).

Phytoplankton

Lake Peipsi is inhabited in all ecotopes (pelagial, littoral, periphyton, benthos) by more than 1,000 algal taxa identified up to now: cyanobacteria (*Cyanophyta*) – 186; diatoms (*Bacillariophyta*) – 539; green algae (*Chlorophyta*) – 331 species; and other groups – 138 species. Phytoplankton of open water area consists of about 500 algal species. The species composition in Lake Peipsi is characteristic for large lowland lakes like Ladoga, Onego, Vänern, Vättern, and Mälaren and resembles also that of Ancylus Lake (Davydova, 1981). Diatoms prevailed in the plankton taxonomic composition and biomass during most of the year; however, cyanobacteria exceeded them in summer and autumn seasons in the last decades. A drop in diatoms occurred in Lake Peipsi s.s. from 2000. The abundance of former dominant species in cold seasons, mesotrophic *Aulacoseira islandica* (O. Müller) Simonsen, is decreased at present. At times, eutrophic *Aulacoseira granulata* (Ehr.) Sim. and *A. ambigua* (O. Müller) Sim. occupy an important part in plankton. The unicellular centric species (genera *Cyclotella*, *Stephanodiscus*, *Cyclostephanos*) are also important. Among cyanobacteria, the genera *Microcystis*, *Anabaena*, *Aphanizomenon*, and *Gloeotrichia echinulata* (J.S. Smith) P. Richter cause massive water blooms in favorable weather conditions, particularly in nearshore areas as well as in the southern hypertrophic lake parts. Nuisance cyanobacterial blooms

are not a phenomenon of the modern industrial society. Massive development of cyanobacteria was noticed in Lake Peipsi sometimes since 1895 (review Laugaste et al., 2001). The share of cyanobacteria in phytoplankton biomass increased during the last decades from 20% to 60% in Lake Peipsi s.s., and from 30% to 90% in the southern parts of the lake in summer months (Haberman et al., 2010). In recent years, strong and long-lasting (up to November) algal blooms were repeatedly observed in the lake. Depending on weather conditions, the duration of algal blooms has increased. Along with continuous hot weather and decreasing water level, the abundance of algae increased in July–August 2002 and the Chl *a* content in the nearshore water reached 400 mg m^{-3} and the phytoplankton biomass 250 g m^{-3} in July–August (Kangur et al., 2005). The ecological situation in the lake worsened quickly and led to a strong fish kill. High concentrations of cyanotoxins were determined repeatedly in Lake Peipsi water during cyanobacterial blooms. Microcystins were identified in bloom samples, when *Anabaena* spp. and *Microcystis* spp. dominated in Lake Peipsi (Tanner et al., 2005). Maximum concentrations of microcystins in water were determined on September 8, 2002 ($586 \text{ } \mu\text{g L}^{-1}$), and on July 5, 2005 ($65 \text{ } \mu\text{g L}^{-1}$). No microcystins were found in the samples from massive bloom of mainly *G. echinulata* in summer 2002.

Zooplankton

In zooplankton species composition and abundance, important changes have occurred during the last century. The species of oligotrophic waters *Holopedium gibberum* Zaddach lived in Lake Peipsi from 1909 to 1964, but it has not been encountered there later. Until the 1930s, no juvenile *Dreissena polymorpha* (Pallas) were found in the zooplankton of Lake Peipsi because adult *D. polymorpha* did not yet inhabit this water body. The cladoceran species *Daphnia galeata* Sars is found in the lake since 1950 (Haberman, 2001).

At present, with respect to number, small rotifers (*Rotatoria*) dominate in Lake Peipsi zooplankton throughout the year, while with respect to biomass, considerably larger cladocerans (*Cladocera*) and copepods (*Copepoda*) prevail, especially *Eudiaptomus gracilis* (Sars) and species of genera *Daphnia* and *Bosmina*. In spring (May), rotifers and copepod juveniles prevailed; in summer and autumn, the species of the genera *Daphnia*, *Bosmina*, and *Eudiaptomus gracilis* (Sars) were commonly dominating, but their biomass was different. In early summer (June) and in late summer (September), the role of the genus *Bosmina* and copepods in the zooplankton biomass was greater than in July when cladocerans, particularly *Daphnia cucullata* Sars, were prevalent. Zooplankton biomass in summer (mean values for July–August, 1997–2006) was 2.23 mg L^{-1} and abundance was 510 ind. L^{-1} .

In parallel with increasing cyanobacterial blooms, an essential decline occurred in zooplankton. A significant decrease in the biomass of all zooplankton groups – cladocerans, copepods, and rotifers – occurred from

2001 (Haberman et al., 2010). The most essential decline affected rotifers. The abundance of *D. polymorpha* veligers also decreased significantly in the whole lake. The decrease in the amount of zooplankton reflects deterioration of lake water quality. The effect of planktivorous fishes on the zooplankton was significant in the 1960s when the fish community was dominated by planktivorous vendace and smelt. However, the recent decrease in zooplankton cannot be explained by the increased pressure of fishes due to vanished populations of planktivorous fish (Kangur et al., 2008a). However, cyanobacterial blooms and presence of cyanotoxins are probably the main reasons for the significant decrease in the amount of zooplankton, particularly rotifers (Haberman et al., 2010).

Zoobenthos

The three main groups of macrozoobenthos in Lake Peipsi are *Chironomidae* (with 111 taxa), *Mollusca* (83), and *Oligochaeta* (59) which form more than half of the species number (Kangur et al., 2008b). The abundance and biomass of macrozoobenthos (average without large mollusks $2521 \pm 96 \text{ ind. m}^{-2}$ and $12.3 \pm 0.5 \text{ g m}^{-2}$ in 1964–2006) as well as species diversity are continuously high in Lake Peipsi. Excluding large clams, chironomids and oligochaetes are dominating in the bottom fauna. The typical community of eutrophic lakes dominated by *Chironomus plumosus* (L.) (*Chironomidae*) and *Potamothenis hammoniensis* (Mich.) (*Tubificidae*) has inhabited the profundal of Lake Peipsi presumably during hundreds of years. Small bivalves of the families Pisidiidae and Sphaeriidae are still abundant in the profundal. Several oxyphilous species characteristic of mesotrophic or oligotrophic lakes, as chironomid larvae of *Monodiamesa bathyphila* (Kieffer) and oligochaetes *Lamprodrilus isoporus* Mich., *Tasserkidrilus acapillatus* (Finog.), *Peipsidrilus pusillus* Timm, and *Limnodrilus profundicola* (Verrill), are present in Lake Peipsi. However, the introduction/invasion of alien species has irreversibly changed the benthic invertebrate community of Lake Peipsi. The zebra mussel *D. polymorpha* that invaded Lake Peipsi in the 1930s (Mikelsaar and Voore, 1936) forms now the most significant animal population of the lake in terms of biomass. The biomass of zebra mussel exceeds the biomass of all other bottom animals about 20 times. The impact of zebra mussel on water quality in Lake Peipsi, through the filtration of phytoplankton and increasing the sedimentation rate of suspended matter, is significant. However, zebra mussels and also zooplankton cannot feed on large colonies of cyanobacteria. The Baikalian amphipod *Gmelinoides fasciatus* (Stebbing), a successful invader in Europe, was introduced into Lake Peipsi with the intention to improve the feeding base of fish in the 1970s. The newcomer was at first explosively distributed near the site of introduction in the eastern shore of the lake and followed by the distribution in the western shore in the 1980s (Timm and Timm, 1993). Until the 1970s, only two gammaridean species occurred in Lake

Peipsi: *Gammarus lacustris* Sars, among macrovegetation and stones in the littoral, and *Pallasiola quadrispinosa* Sars, in open sand bottom habitats. Intentional introduction of *G. fasciatus* from Siberia has irreversibly altered littoral benthic communities in Lake Peipsi. At present, *G. fasciatus* is the most abundant macroinvertebrate species in the nearshore area, while the native gammarids *G. lacustris* and *P. quadrispinosa* appear to be extinct and oligochaetes have declined (Kangur et al., 2010). The distribution pattern of the invader close to water edge in summer makes it mostly inaccessible for adult fish. Being highly mobile, *G. fasciatus* is not sensitive to water level fluctuations in shallow lakes. These characteristics increase its success.

Fish community characteristics

Lake Peipsi is inhabited by 37 fish species (Kangur et al., 2008a). Over the past 80 years, no species have been lost from Lake Peipsi; on the other hand, there is neither any information about invasion of new species into the fish community. Lake Peipsi has been rich in fish production, where smelt, *Osmerus eperlanus eperlanus* m. *spirinchus* Pallas; vendace, *Coregonus albula* (L.); and pikeperch, *Sander lucioperca* (L.) have been the main commercial fishes in the lake at different times. However, despite the same species composition and interannual variations, the commercial fish catch was seen to decline to about half of the catches taken 80 years ago. According to commercial statistics, the average annual catch of fishes was 11,650 t (33 kg ha⁻¹) in 1931–1940 and 5,593 t (e.g., 16 kg ha⁻¹) in 2005–2009. In addition, substantial alterations in relative species dominance have been noted. In the 1930s, the main commercial fish were smelt (43% of total catch); roach, *Rutilus rutilus* (L.) (16%); perch, *Perca fluviatilis* L. (7%); and bream, *Abramis brama* (L.) (7%). In 2005–2009, most of the commercial catches comprised pikeperch (34%), bream (17%), roach (14%), and perch (13%). Less abundant commercial fish species were pike, *Esox lucius* L.; burbot, *Lota lota* (L.); and ruffe, *Gymnocephalus cernuus* (L.). Peipsi whitefish, *Coregonus lavaretus maraenoides* Poljakow; vendace; eel, *Anguilla anguilla* (L.); rudd, *Scardinius erythrophthalmus* (L.); ide, *Leuciscus idus* (L.); tench, *Tinca tinca* (L.); and white bream, *Blicca bjoerkna* (L.) have been occasionally represented in catches. The Red Book of Estonia (2011) includes wels, *Silurus glanis* L.; grayling, *Thymallus thymallus* (L.); bullhead, *Gottus gobio* L.; asp *Aspius aspius* (L.); mud loach, *Misgurnus fossilis* (L.); vendace; and Peipsi whitefish.

Fish stocks of Lake Peipsi are mainly affected by (1) overexploitation, by (2) ecosystem changes (e.g., eutrophication, degradation in water quality, siltation of spawning grounds, shifts in food webs), and also by (3) natural processes (e.g., heat waves, increases in water temperature, changes in ice conditions, fluctuations in water level). Concurrent worsening ecological conditions in Lake Peipsi and high fishery pressure (including pouching, unregistered caught quantities, excessive

number of professional fishermen) is threatening fish stocks, causing a substantial decrease in catches and triggering changes in community structure. The effect of fishing is the most important human impact on the fish community in Lake Peipsi. Even though the fishery methods have changed, the fish stocks of the lake have repeatedly suffered from the overfishing (Kangur et al., 2007a). Investigations made by von Baer (1852) in the middle of the nineteenth century targeted the reasons for the declining stocks and catches of main commercial fish species (mainly bream) in Lake Peipsi and concluded that the main reason was the intensive use of fine-meshed towed fishing gear as well as the blocking of the spawning migration routes of bream by large traps. In the 1950s, fishing was markedly intensified in Lake Peipsi due to high demand for food after WW II. Therefore, trawling was reintroduced in the lake and expanded drastically. Extensive use of fine-meshed towed fishing gear (e.g., trawls replaced later by bottom seines) affected mostly recruitment of pelagic predator, pikeperch, killing young specimens of this fish in large quantities. The next drastic increase in fishing pressure was caused by the sociopolitical changes brought along with the collapse of Soviet Union. At the beginning of 1990s, fishing became a highly significant source of employment. Therefore, the number of fisherman doubled in comparison with the end of Soviet period. During the last decade, the fishery in the lake is regulated according to the Estonian–Russian Fisheries Agreement from 1994, whereas since 2000, quotas are established for all commercial species.

Fishery has direct negative impact on the total stock and on the size composition of the fish community. Particularly, pikeperch population is affected because larger specimens are almost completely removed leaving an unbalanced population of only a few young year-classes. Substantial decrease in the abundance of larger specimens of pikeperch in L. Peipsi means that the predatory pressure of its stock has changed and directed to smaller prey. Human-induced imbalance within fish stocks (e.g., change of predator versus prey proportions) has cascading effect through food webs. The ecological role of top predators as the main regulators of the abundance of coarse fish has diminished.

Although the population dynamics of several fish species, especially of big predators, is to a large extent controlled by fishery, the long-term effects of concurrent eutrophication and environmental extremes (e.g., heat waves, water level fluctuations, changes in ice conditions) on the fish community are considerable. Since the 1930s, several marked changes occurred in the composition of fish community. By the turn of the decade 1980/1990, a sharp decline in vendace population coincided with a major increase of pikeperch. The abundance changes in the Lake Peipsi fish community have gone in opposite directions for cold-adapted as compared with warm-adapted species (Kangur et al., 2011 submitted). The fish community has shifted on a long-term scale from clean- and cold-water species like smelt, vendace, whitefish,

and burbot toward more pikeperch and bream, which prefer productive warmer and more turbid waters. Lake Peipsi is no longer a suitable habitat for smelt, vendace, whitefish, and burbot, which prefer colder oligotrophic water and that richer in oxygen. However, the new conditions are suitable for pikeperch and bream, which are generally classified as warm-water-tolerant species favored by eutrophic conditions. Although the fish species list has not changed in Lake Peipsi during the last decades, there have been significant shifts in relative dominance and in the prevalent feeding habits of the fish species. A major decrease in pelagic planktivores (e.g., smelt, vendace, Peipsi whitefish) can be considered as the main indicator of such significant shifts.

Besides small, systematic trends that have become important in the longer term, major abrupt changes have occurred repeatedly during the last half century in the Lake Peipsi fish community. Concurrent eutrophication and sudden environmental extremes (e.g., heat waves) can cause long-lasting and irreversible changes in the fish community of the lake. In Lake Peipsi, the effects of eutrophication have seemed to increase dramatically in hot and dry summers, when water level decreases sharply, and all the usual water quality parameters (e.g., water transparency, nutrient content) have demonstrated the worsening of the lake's ecological health (Kangur et al., 2005). Thus, the lake's status can shift abruptly, e.g., in response to drought, causing unexpected catastrophes in its biota (e.g., fish kills). Current data indicate that recent climate warming in summer time (together with severe heat waves) and nutrient enrichment in the Lake Peipsi ecosystem are acting in the same direction: both are increasing the probability of fish kills, which have become more frequent and extensive. In the summers when cyanobacterial (blue-green algae) blooms, hot and calm weather, and consistently high water temperature (up till 26–28°C) co-occur, fish kills have been repeatedly observed in Lake Peipsi over the past five decades. Although mass growth of cyanobacteria has been documented in the lake since the nineteenth century (Laugaste et al., 2001), eutrophication (the addition of the nutrients to the lake) appears to have raised the intensity of the blooms. A fish kill during a bloom of *Aphanizomenon* sp. was first described in 1959, when a sudden large-scale smelt mortality occurred in the southern part of the lake, Lake Pihkva (Semenova, 1960). The next massive smelt kill in summer 1972, during a calm warm period and strong cyanobacterial bloom, affected the entire lake. In the following years (1973–1974), no smelt were caught; however, a quick recovery of stock occurred in the following 2–3 years. In a similar fashion, subsequent hot summers with cyanobacterial blooms had long-term negative effects on the smelt population. In recent years, the abundance of smelt population has reached a historically minimum level. After extreme weather events and fish kill in 1988, the vendace population collapsed and has not yet returned to its previous levels. Recently, however, besides cold-water fish (smelt, vendace), other fish species, especially

bottom-dwelling fish such as ruffe and juvenile fish of several species, were also seriously affected by concurrent effects (Kangur et al., 2011 submitted). During the fish kills in 2002 and 2010, ruffe has been seriously affected. This may be due to the fact that the heat waves and cyanobacterial blooms can lead to the bottom layers of the lake water becoming oxygen-deficient. As environmental extremes have become more frequent and summer fish kills have involved larger area, there was serious damage to the fish populations which eventually may lead to the extinction of some fish species (Kangur et al., 2011 submitted). This has already been proven to be correct for smelt, a previous key species in the fish community.

Socioeconomic significance

Lake Peipsi is of great economic significance, first of all as the drinking water source for the Estonian industrial town Narva and its sister town Ivangorod on the Russian side of the border, but also in terms of water transport, fishery, and energy production. Its bottom deposits hold great reserves of curative mud and building materials, and its waters cool the huge kettles of the Baltic and Estonian Thermal Power Plants and drive the turbines of the Narva Hydropower Station. The beaches of the lake, especially in the northern and eastern parts, have a big recreational value. Fishing is an important sector of rural employment in the Peipsi region and an essential part of the lifestyle in the lake's coastal villages. Fish stocks of the lake have been remarkably high, which makes it economically important for both commercial and recreational fishermen.

History of research

Hydrobiological studies on Lake Peipsi have a long tradition; fishery investigations began already with the work of Karl-Ernst von Baer in 1851–1852. Since 1950, systematic hydrochemical studies are carried out on the lake. Annual hydrobiological monitoring of Lake Peipsi has been carried out by the Institute of Zoology and Botany since 1962 and monitoring of coasts by the Institute of Geology since 1981. Today, this work is part of the Estonian State Environmental Monitoring Programme, which gained legal ground in 1993. The results of the monitoring constitute the main scientific base for political decisions to be passed by the state and local authorities. Unfortunately, most studies since 1992 have been on the Estonian part of the lake. However, regular joint Estonian–Russian expeditions to the whole lake have been arranged since 2001. Several monographs about Lake Peipsi have been published during the last decade (Miidel and Raukas (1999); Nõges (2001); Pihu and Haberman (2001); Haberman et al. (2008)).

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Cross-references

Climate Change Effects on Lakes
 Climate Change: Factors Causing Variation or Change in the Climate
 Finnish Lakes
 Nutrient Balance, Light, and Primary Production
 Russian Lakes
 Russian Lakes, Geographical Classification
 Võrtsjärv Lake in Estonia
 Water Balance of Lakes

PHOSPHOR EXCHANGE SEDIMENT-WATER

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Introduction

Lake sediments play a crucial role in the phosphorus metabolism in lakes. The impact depends on the capacity to retain and thereby decrease the phosphorus availability in the lake water and secondly, on the ability to release phosphorus when environmental conditions change. The particle composition, prehistory, and binding capacity of the sediment govern its behavior. The general view until the 1970s was that sediments acted as sinks for phosphorus with the exception of periods with anoxia in the bottom waters, when iron-bound phosphate is released to the hypolimnion of stratified lakes (Einsele, 1936; Mortimer, 1941, 1942). During the last decades, more knowledge has been gathered (Boström, 1982; Löfgren, 1987; Rydin, 1999) and a much more complicated picture has developed, emphasizing the important role of internal loading for lake water quality and especially for the summer blooms of cyanobacteria in lakes.

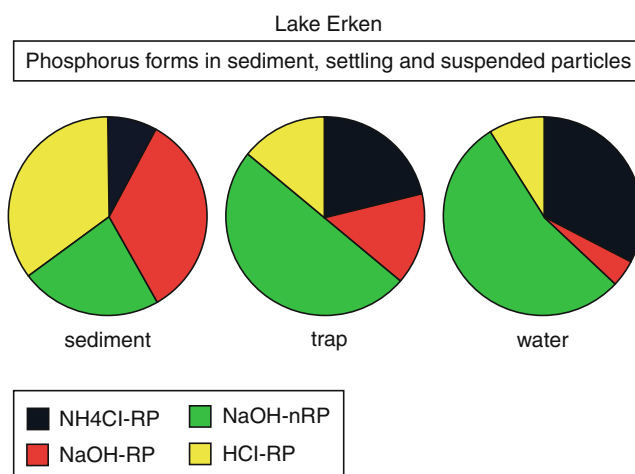
The internal loading from lake sediments will often determine the level of eutrophication of the lake and the time lag for recovery after reduction of the external loading. Internal loading is most important during summer when the water temperature is high, speeding up the lake processes. The pool of phosphorus bound to particles in the surficial sediments (10 cm) is vast (100 fold) in comparison to the phosphorus pools in the water column. Phosphorus can leave the sediment in a dissolved state mainly as phosphate or as particles. In the latter case, there are two major ways: as resuspended sediment particles (detritus) or by migration of resting stages of phytoplankton. Even if a very small share is released, it will have significant impact on the phosphorus concentration in the lake water.

The distribution of phosphorus forms in sediments has been investigated since the 1950s. Generally, vertical profiles of sediment phosphorus concentration, expressed on a dry weight basis, show an increasing concentration toward the sediment surface in eutrophic lakes. This increasing vertical profile continues into the water, when looking at sedimenting particulate matter (sedimentation

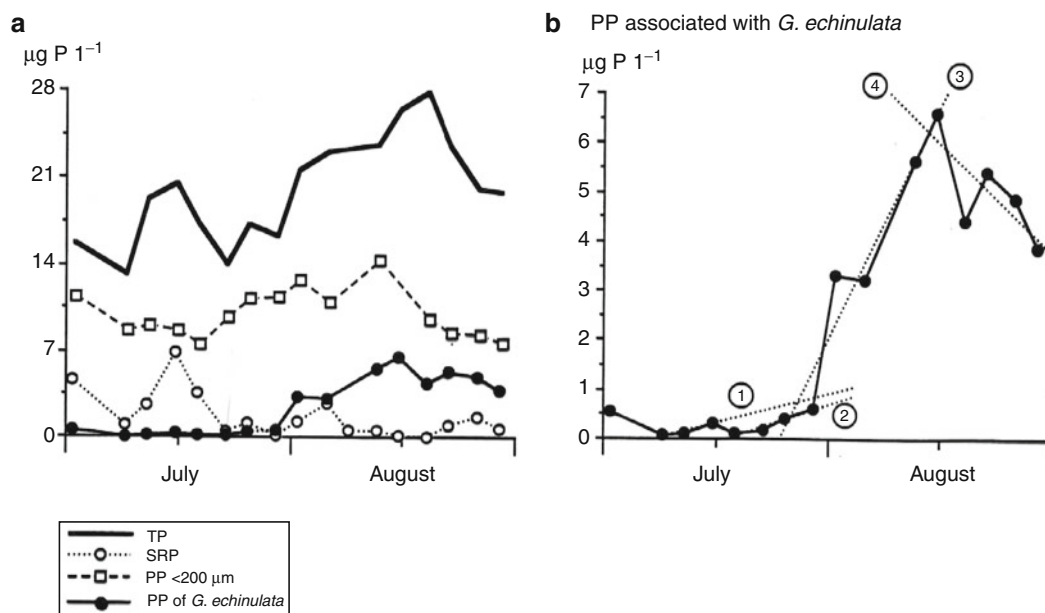
traps) and suspended matter. The different phosphorus forms are determined by sequential extraction and labile, aluminum-, iron-, and calcium-bound phosphorus can be separated. The residual is mainly organically bound phosphorus. Organic as well as iron-bound and labile phosphorus are the three fractions increasing in the vertical profile mentioned above. An example of the fractional phosphorus composition from Lake Erken, Sweden illustrating this is shown in Figure 1.

A number of environmental factors are important in the mobilization process. To leave the sediment in a dissolved state, phosphorus must be mobilized by physical, chemical, or biological processes and then transported to the lake water. The splitting mechanisms includes desorption, dissolution of precipitates and complexes, ligand exchange, and enzymatic hydrolysis of organic ester bonds. Most studies indicate that sediment bacteria have a significant role in uptake, storage, and release of phosphorus including anaerobic release of iron-bound phosphorus. The redox potential in the sediments affects reduction of iron (III) to iron (II) and a subsequent release of phosphate. At higher pH levels (i.e., in shallow lakes with high primary production), hydroxide ions replace phosphate causing ligand exchange. A high water temperature increases the bacterial activity giving lower redox potential and a higher production of enzymes. This means that phosphorus can be released from lake sediments although the oxygen concentration in the water is high when the water temperature is high during summer.

Several phytoplankton species have resting stages overwintering in the sediment. When growth is induced, they leave their habitat in order to shift their life form to a pelagic one. In Lake Erken, Sweden, the cyanobacteria *Gloeotrichia echinulata* has been shown to contribute to



Phosphor Exchange Sediment-Water, Figure 1 Phosphorus forms in sediment, settling, and suspended particles in Lake Erken, Sweden.



Phosphor Exchange Sediment-Water, Figure 2 Increase of total phosphorus concentration in Lake Erken and the contribution of migrating *Gloeotrichia echinulata*.

the internal loading of phosphorus during summer. The floating capacity of the colonies makes them able to pass the metalimnion and migrate to the epilimnion, transferring phosphorus from sediments to the upper water strata (Figure 2).

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[Nutrient Balance, Light, and Primary Production](#)

PLAYA LAKE CHAINS: THE EXAMPLE OF THE YENYENING LAKES OF THE UPPER AVON RIVER CATCHMENT OF WESTERN AUSTRALIA

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Introduction

The term “playa” or “pan” applies to individual arid zone basins of varying size and origin that are subject to ephemeral surface water flows (Shaw and Thomas, 1989) such that lakes may occur within playas as permanent or ephemeral features. Playas in Australia are often geologically young (Quaternary) features developed in arid environments and are often dry due to evaporation (Boggs et al., 2006). Although playas are a response to tectonics, climate change, and eolian and fluvial processes, the majority of the scientific literature considers either their origin within a regional context, or the development dynamics of individual playas (e.g., Bettenay, 1962). However, where playas are developed within paleodrainage channels, they may exist as isolated features, but more often they exhibit a degree of hydrological interconnectivity with other playas to form “playa chains” such that the development history of an individual playa cannot be addressed without consideration of its neighbors.

Dryland salinity is a major environmental issue in inland Australia, particularly in Western Australia and South Australia, and has been estimated to affect over 2.2 million hectares (State Dryland Salinity Committee, 1990). The Wheatbelt region of the southwest of Western Australia has the largest area of land affected by salinity, and this is predicted to increase to 8.8 million hectares by 2050 (Australian Natural Resources Atlas, 2000). Isotopic studies have shown that some salt in the soils are of marine origin and accumulate by winds transporting salt inland from the sea (Chivas et al., 1991). However, in this region the replacement of deep-rooted perennial species with shallow-rooted annual cropping species (Wood, 1924; Mulcahy, 1978; Schofield et al., 1988) has resulted in waterlogging and extensive salinization of rivers, streams, and valley floors. The reduction in evapotranspiration associated with widespread land clearing led to a rise in the level of the saline aquifer and mobilization of salt previously stored deep within the soil profile.

Prior to clearing, Wheatbelt catchments were essentially completely vegetated with a diverse range of woody plant communities whose distribution was controlled by climate and soil type (Beard, 1981). The vegetation was capable of using deeply infiltrated water during the dry season. Most of the annual precipitation was evaporated or transpired. However, there is anecdotal evidence that the drainage systems prior to the twentieth century were fresh or at least less saline than today (Cross, 1833; YLMS, 1996) with well-vegetated riparian zones. With clearing, the water balance changed to one of reduced annual evaporation and interception and increased runoff and recharge (Hatton et al., 2003). Runoff onto and through valley floors is considered to have increased by a factor of 5, and increased groundwater recharge is filling deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on slopes and ridges with additional hydraulic heads forcing groundwater toward the valleys and resulting in increased discharge of water and salt to streams and wetlands. The changes in local climate due to forest removal and the reduction in vegetation cover must also have implications for eolian processes. The Yenyening Lakes and Salt River sections of the Upper Avon catchment (Figure 1) form a series of interconnected playa lakes and seasonally wetted salt pans confined within a paleochannel. The Yenyening Lakes are part of a regional complex of playa lakes (Killigrew and Gilkes, 1974) that only recently have received detailed scientific scrutiny (e.g., Boggs et al., 2006). The Yenyening Lakes are considered to be a very significant feature in the hydrology of the Wheatbelt (WRC, 2002) because all the drainage of the Lockhart and Yilgarn catchments (which cover a significant portion of the region) flows through them into the Avon–Swan system. Significantly, the morphology of the playa chains is a response to the geology and the present climatic, topographic, and hydrographic

controls, but also the morphology has characteristics inherited from prior climatic and hydrological systems that require elucidation.

Climate and hydrology

The regional climate is characterized by hot, dry summers and warm, wet winters (Gentili, 1971, 1993). The average annual rainfall in the region is 350 mm, and the average annual evaporation is approximately 2,100 mm (WRC, 2002). Prevailing winds are strongest from the southwest during summer but from the northeast during winter.

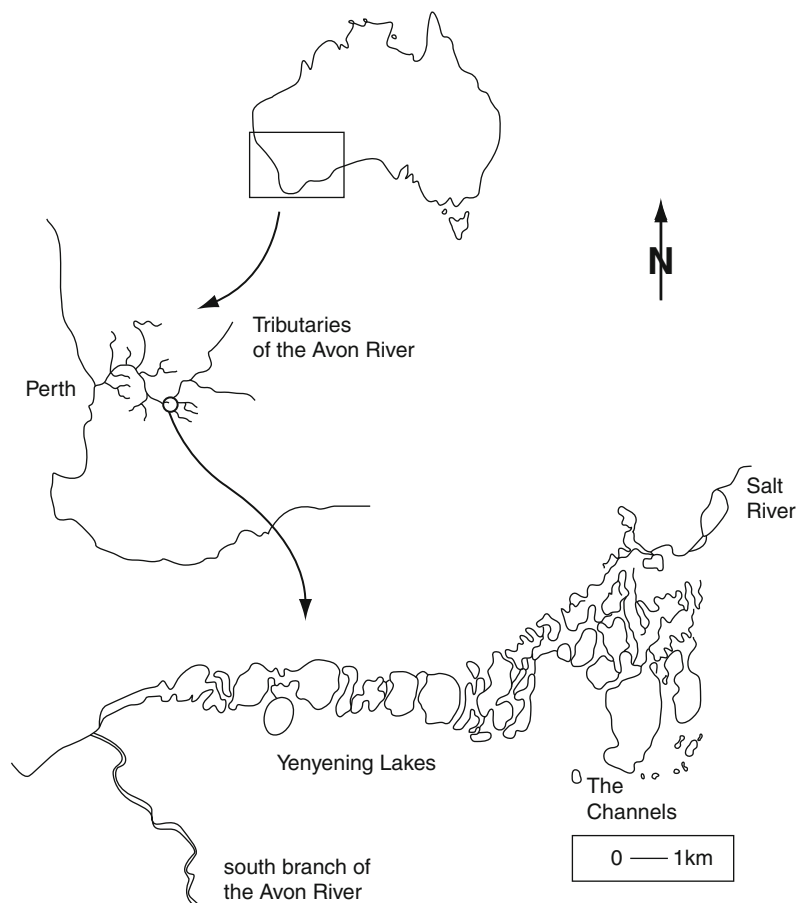
Although the name “Salt River” suggests that river has always been saline, this epithet probably referred to the episodic pulses of salt that would have moved through the river when sufficient rainfall occurred in the uppermost areas of the catchment to move salt water through from playas much further to the east and south, such as Lake Deborah and Lake Grace.

A simple salt and water balance model for the Yenyening Lakes System was developed by Bari (2002) from data available over the period 1973–2000. During that period there was an average annual inflow of 39.5 million cubic meters and outflow occurred in most years. Approximately 92% of the total annual input was lost by flow out to the Avon River and 8% by evaporation processes. Loss through seepage to the deep aquifer was considered to be negligible. The median salinity of the playas was 60,000 mg/L TDS, the annual average salt input was 381,000 t, and 99% of the stored salt was lost due to overflow.

The Yenyening Lakes Management Strategy (WRC, 2002) suggested that the generalized description of groundwater hydrology in the Wheatbelt can be applied to the Yenyening system. Prior to forest clearance, the hydrological system was in balance with the water table maintained at a constant depth and the native vegetation able to use all of the rainfall infiltrating the soil profiles. This situation was dramatically altered through land clearing. The water table has risen and the discharge of saline groundwater to the surface drainage has increased. A substantial area with depth to groundwater from 0.5 to 1 m adjoins the main drainage line, and the playas, channels, and the Salt River are considered to be fully saturated (Smith, 2002). Land Monitor (2000) plots indicated that the area of salinized land in the region had increased between 1989 and 1998 and would continue to increase significantly (Smith, 2002).

Geology and geomorphology

The geology and geomorphology of Western Australia was summarized by White (2000), who noted that satellite imagery reveals that the modern landscape contains a mixture of ancient and modern features. Many modern rivers and playas are in the valleys of ancient paleodrainage lines. The paleodrainage patterns of the state were established by the end of the Cretaceous or early in the Tertiary (65–60 million years ago) (Van de Graaff



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Figure 1 Location of the study area in southwestern Australia. The *inset box* shows the location of the Avon River tributaries and the Yenying Lakes. The *inset circle* shows the chain of playa lakes located between the south branch of the Avon River and the Salt River.

et al., 1977; Zheng et al., 1998). White (2000) recognized seven major paleodrainage provinces on the Yilgarn Craton. The province in which secondary salinization has been particularly prevalent is that of south-to-north trending valleys that drain into rivers flowing into the Indian Ocean (the Avon–Swan and Canning Rivers).

A comprehensive study of the geomorphology, geology, and paleohydrology of the Salt River system by Salama (1997), within the context of the regional development of the drainage system (Beard, 1999, 2000), noted that the Salt River system connects the saline playas of the Yilgarn catchment in the eastern ancient zone with the rejuvenated Avon–Swan system in the west and has probably occupied the same course since the early Tertiary. At that time, the uplift of the Yilgarn Craton and the formation of the Darling Scarp dammed the river and caused the formation of a large inland lake. This large paleolake at Yenying (named Yilgarn Lake) persisted until the opening of the northern outlet of the Avon which occurred during exceptionally wet periods after denudation reduced the height of uplifted areas (Salama, 1997).

Smith (2002) noted that the geology of the system was mapped by Chin (1986a, b). Sand plain and laterite occur at higher elevations while the valleys contain Holocene alluvium and Cenozoic sediments. The basement comprises medium to coarse adamellite, gneiss, rare dolerite, and quartz dykes some of which crop out as rocky knolls.

Today the Yilgarn and Lockhart Rivers merge at Caroline Gap to form a broad valley floor containing the Salt River and, further downstream, the Yenying Lakes. The two catchments comprise about 91,000 km² of mainly cleared agricultural land (WRC, 2002). Overflow occurs into the Avon River at Qualandary Crossing. The crossing was constructed in the early 1900s and acts as a weir to prevent backflow from the Avon River. The current gated culvert was completed in 1998; the gates are opened under moderate flows while flood events pass over the top of crossing (WRC, 2002).

A series of oblique color aerial photographs of the Yenying Lakes were available from ten low-level flights undertaken by one of us (JD), in different seasons, between October 2002 and May 2004. The photographs

were used to determine the patterns of inundation in the salt playas and across the Salt River valley floor, the shape of the playas and the degree of interconnectivity, and the presence and extent of retentive features, such as sandy banks and lunettes. Lunettes are the windblown ridges of fine sediment that often accumulate on the downwind margins of seasonally dry lakes due to deflation of the dry lake bed (Bowler, 1973). Remotely sensed imagery revealed the extent of inundation following a major episodic rain event throughout most of the catchment in January, 2000. A field visit which followed the Salt River, upstream, from Yenyening Lakes to Caroline Gap was undertaken in May 2004 to ground truth aspects of the aerial photographs.

A series of channels and playas of various sizes occur immediately upstream of Qualandary Crossing for a distance of approximately 30 km. Sandy or clay banks and “lunettes” are present. The lunettes are relatively bright on air photography; rise between 1 and 3 m above the dry season water level (DSWL – as noted in 2004) are arcuate in planform and usually are best developed on the downwind side of a given playa. The sandy banks, usually rising less than 2 m above the DSWL, often occur as a collection of several subparallel ridges that are particularly obvious at low water levels. Those within the lakes appear to be lunettes that formed during lower lake levels but have been submerged by a rise in the water level. Both the sandy banks and lunettes are actively developing as witnessed by blowing sand and the presence of recent wind ripples on their surfaces in 2004. However, the effects of river flow and wind-driven water circulation must also play a role in the formation and morphological evolution of these banks as often they are more linear in plan view than neighboring lunettes. Figure 2a reveals the presence of both banks and lunettes within lakes and channels throughout the system. A number of well-defined linear banks are present within The Channels and adjoining unnamed lakes (Figure 2b). The lower banks and lunettes are devoid of plant life or are dominated by samphires, but some of the higher ones, for example, those at Ossig’s Lake, contain shrubs and trees.

The pattern of bank and lunette formation evident at Ossig’s Lake under low water conditions, in March 2004, revealed the influence of both eolian and fluvial processes (Figure 3a). The direction of water flow is from bottom right to top left, the northeast, while the predominant wind direction in summer (Figure 3b) is from top left to bottom right, the southwest. Thus wind-driven mixing, acting against the direction of any residual river flow, will predominate during summer. High river flows will be in the same direction as the dominant winds (northeasterly) during winter. Further upstream the geomorphology of the valley floor changes to that of fewer and smaller pools and finally to a network of complex, shallow channels. It is likely that the rise in the saline water table has resulted in greater definition of the shallow, diffuse channels. Under previous, less waterlogged conditions, many of

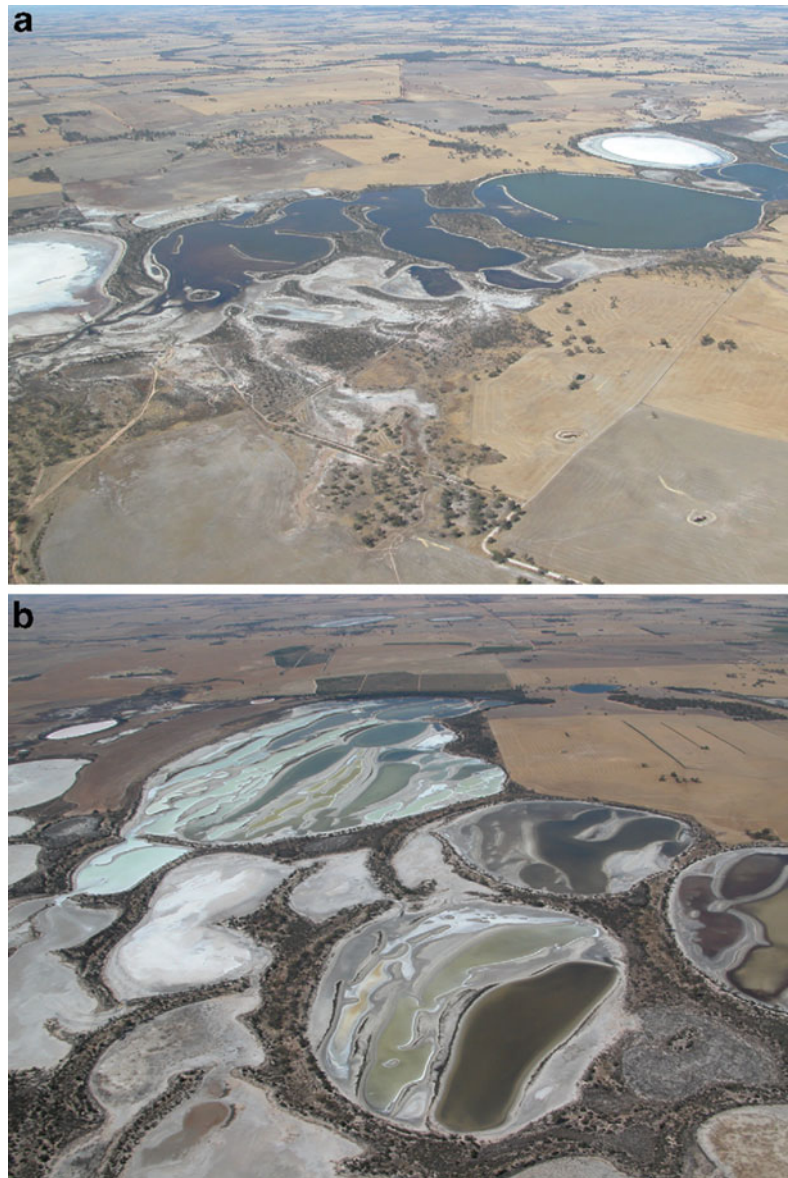
these shallow channels may have been predominantly dry and would have supported low, terrestrial plant communities.

The evaporation from the shallow water table which concentrates the salts in groundwater near the surface and accumulates them in the soil, as described by Smith (2002), is demonstrated by the white areas of salt prominent on the valley floor margins in Figure 2b.

Under conditions of high flow, many of the banks are submerged; however, those banks and lunettes containing well-developed plant communities are likely to be rarely flooded. A field visit in May 2004 demonstrated that although many banks and lunettes are submerged during high river flows, their morphology should still exert a major control on the direction of water flow, mixing processes, and retention times. Whereas small banks tend to be approximately parallel to the direction of flow, high banks also occur that are transverse to the direction of stream flow. These few very high banks are stable features, with good soil development and relict woodland, and occur as breached barriers between successive major salt lakes. These banks appear to consist of amalgams of two or more “fossil” lunettes, developed on a scale in excess of the smaller, active lunettes within the lakes; they rise to around 20 m above the DSWL. In each case, a single channel cuts through each bank, thus connecting contiguous lakes. These high banks were not inundated by the exceptional flood of January 2000. This conclusion may be drawn from the evidence of water levels in the satellite images and also from wrack marks consisting of accumulations of shells of the gastropod *Coxiella*, which are around 2 m above the DSWL.

Large lunettes developed in SE Australia between 17,000 and 15,000 B.P. (Bowler, 1973). No dates are available for the Yenyening banks, but it is hypothesized that these fossil lunettes developed in the late Quaternary and/or Holocene and are evidence for seasonal desiccation of these chains of lakes, even if the water flow at that time was less saline. The presence of these large banks separating individual lakes affords a considerable degree of retention to water flow down through the system, both through constraining surface flow to a single connecting channel but also almost certainly inducing shallow groundwater seepage between adjacent lakes.

Small lunettes and the lake margins are visibly subject to wind action as wind-blown sand and eolian ripples were observed in 2004. Nevertheless there is no clear morphological relationship between the lunette and lake plan views and the prevailing wind direction. Thus a more detailed analysis of the orientation, morphology, stratigraphy, and sedimentology of the smaller lunettes and linear banks with respect to the prevailing winds is needed to fully elucidate the processes by which these structures have formed. Similarly the large wooded banks separating many of the lakes are one order of magnitude higher than the small active lunettes and of considerable bulk. These are hypothesized to be lunettes that formed under prior wind and hydrological regimes.



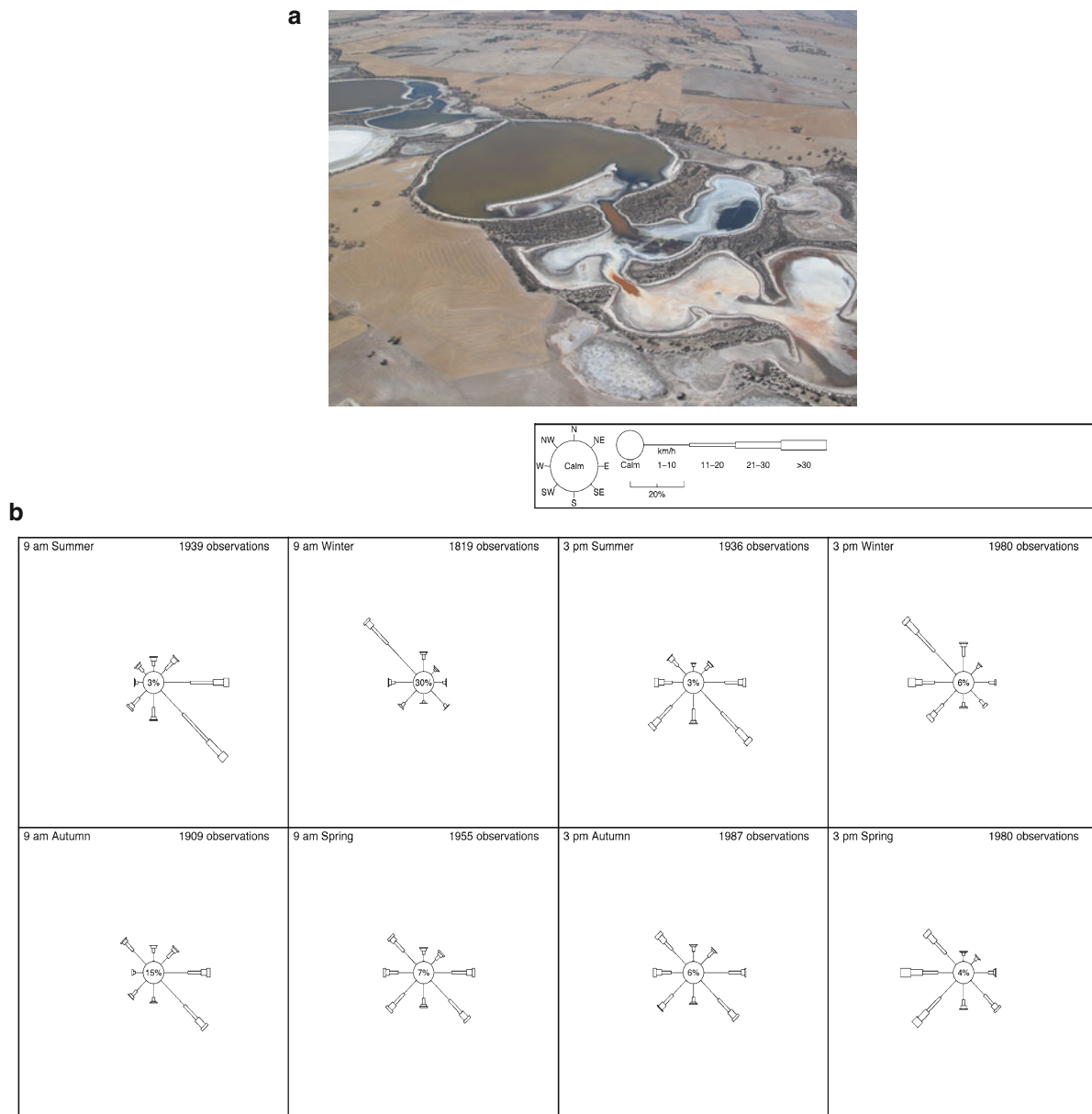
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Figure 2 (a) *Right to left:* Racecourse Lake (dry with white salt crust), Ossig's Lake, The Neck, and Mud Lake (dry). Morbining Gully in the foreground. Direction of flow is from left to right. Oblique view from the northeast, December 22, 2003. (b) *The Channels.* Flow in this region is diffuse but overall direction is from left to right. Oblique view from the north, December 22, 2003.

Notwithstanding the lack of detailed data, the information revealed by aerial photography and ground survey is sufficient to indicate that the lunettes and banks are an important structural component of the Yenying Lakes system that records the history of lake and drainage network development as well as controlling modern-day retentiveness.

Evidence of freshwater seeps along the margins of the valley floor were also evident (through distinctive color changes) in some aerial photographs. The healthy plant communities present on the southwestern corner of The Channels indicated the presence of freshwater discharging from the adjacent slope. Whether this area will be

enhanced or degraded by the recent planting of maritime pines (*Pinus pinaster*) on the privately owned adjoining slope is not known. This area appeared to contain the best example of healthy vegetation within the entire reserve and deserves further investigation. Freshwater seeps were noted elsewhere using aerial photography and one, at Yenying Lake, had a considerable surface flow. These seeps are of considerable nature conservation value, have local agricultural value, and have a currently undefined effect on dilution of low-flow saline waters in the valley.

The dry, salt-encrusted states of two lakes (Racecourse Lake and Mud Lake) were found to be due to the diversion



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Figure 3 (a) Ossig's Lake and The Neck under low-water conditions. Direction of flow is from bottom right to top left. Oblique view from southeast, March 19, 2004. (b) Wind roses showing seasonal wind data for Beverley (lat: 32° 06'30"S, long: 116°55'29"E), the nearest weather station to Yenying Lakes. The period of recording was from January 1985 to December 2006. Source of data: Commonwealth of Australia – Bureau of Meteorology.

of water undertaken by a local resident in an attempt to promote flow through the main system. This was undertaken with the expectation that such action would prevent an increase in the salt load in the large lakes used for recreational activities (water-skiing) (T. McLean, pers comm.). This approach to “disconnecting” some lakes from the rest of the hydraulic system to decrease the retention time of water in the rest of the reserve is an unproven technique that might have unforeseen repercussions on the

nutrient status of the water and the ecology of the lakes that remain connected.

Nature conservation, cultural, and recreational values

The nature conservation and recreational values of the lake were described by the Yenying Lakes Management Strategy (1996). The lakes are recognized as an important area for waterbird habitat and breeding, with 41 species

recorded using the lakes, and 10 species are known to breed there (YLMS, 1996). Forty-six land species have been recorded in the lakeside bushlands. The lakes are encompassed by two Nature Reserves; these are vested in the Conservation Commission of Western Australia and managed by the Department of Conservation and Land Management. The main series of lakes lies within Reserve 31837 which was created for the purposes of "Recreation and Conservation of Flora and Fauna." Further upstream is Reserve 28088 which was created for the "Conservation of Flora and Fauna" and contains The Channels and adjoining flats and banks (Yenyening Lakes Management Strategy, 1996).

The first sighting of the numbat (*Myrmecobius fasciatus*), a now rare and endangered marsupial, was recorded from the lakes' area by Ensign Dale (1831) in a letter to the Surveyor-General, J.S. Roe (Cross, 1833). Dale also noted the presence of "an inland lake of freshwater or perhaps a reservoir of the river"... "varied in its breadth from 60 to 70 yards, and 5 or 6 miles in length." Upon reaching this, he described seeing "an immense number of ducks, swans and other waterfowl" (Cross, 1833, p. 156).

The Yenyening Lakes Management Strategy (1996) noted that older local residents remembered the lakes teeming with birdlife and the surrounding woodlands supported native animals and wildflowers. The area was first settled in the 1890s, and degradation due to rising saline groundwaters was observed from the 1930s onward together with the spread of exotic weeds and the arrival of exotic fauna including rabbits, foxes, and feral cats. Although the bushland adjoining the lakes is now considered to be extremely degraded, the numerous sandy banks within the lakes' system appear to be unaffected by salinization, and although weedy, still support a range of local plant species including the salt-tolerant Salt River gum (*Eucalyptus sargentii*) and the Yenyening mallee (*E. vegrandis*). Seed is collected from *E. sargentii* for land rehabilitation programs throughout the southwest (Yenyening Lakes Management Strategy, 1996).

Ensign Dale noted that numerous aboriginal groups were seen in the area (Cross, 1833). Although little specific information appears to have been recorded, the presence of freshwater and abundant wildlife suggests that the lakes were important for indigenous groups.

Early settlers hunted, swam, and picnicked by the lakes, but the current most popular form of recreation at the lakes is water-skiing (Yenyening Lakes Management Strategy, 1996). As a consequence, some of the current management of water levels in the lakes, via the gates at Qualandary Crossing, is undertaken to maintain suitable water depths and water quality for skiing.

Interpretation of the aquatic ecology of the Yenyening Lakes and salt river system from aerial photography

Although the nature conservation values of the Yenyening Lakes are well recognized (Yenyening Lakes

Management Strategy, 1996; Water and Rivers Commission, 2002), little information exists on the aquatic ecology of the lakes. Recent work on the ecology of secondary saline wetlands in the Wheatbelt region by Davis et al. (2003) and Strehlow et al. (2005) suggested that three possible ecological regimes may exist in these systems: clear, macrophyte-dominated; turbid, phytoplankton-dominated; and clear, benthic microbial mat dominated.

The concept of two states, clear water dominated by aquatic macrophytes and turbid water dominated by phytoplankton, has been described in shallow European lakes undergoing eutrophication (Scheffer, 1998; Jeppesen et al., 1990; Blindow et al., 1993; Scheffer et al., 1993; Moss et al., 1996). Davis et al. (2003) extended this approach and identified contrasting aquatic vegetation states that were closely associated with different salinities. They suggested that salinization results in the dominance of a small number of salt-tolerant submerged aquatics (*Ruppia*, *Lepilaena*, *Chara*, and *Lamprothamnium*). With increasing salinity, these systems may undergo further change to microbial mat-dominated systems comprising mainly cyanobacteria and halophilic bacteria.

Because of the difficulties in demonstrating stability and the alternative nature of these states, Strehlow et al. (2005) suggested that the term "ecological regime" should be used *sensu* Scheffer and Carpenter (2003).

Sim et al. (2006a) suggested that the upper limit for submerged aquatics may be as high as 90 mgL⁻¹ TDS. Additionally, however, the submerged aquatics studied so far in Wheatbelt wetlands also appear to have a requirement for a seasonal water regime. Benthic microbial mats appeared to be dominant in seasonal waterbodies at salinities >90 mgL⁻¹ or at lower salinities if a permanent water regime is present. Positive feedback loops are likely to exist such that mats can outcompete (and overgrow) germinating seedlings under a permanent water regime. Conversely aquatics can germinate and seedlings quickly develop as a seasonal wetland refills, effectively disrupting the conditions needed for benthic mat development (Sim et al., 2006b).

An upper limit of salinity has not been determined for turbid, phytoplankton-dominated systems. Moss et al. (1996) suggested that this state is likely to dominate at concentrations of total phosphorus > 150 µgL⁻¹.

Aerial photography revealed the presence of both turbid, phytoplankton-dominated and clear, benthic microbial mat-dominated regimes in the Yenyening Lakes and Salt River system. The different colors present in pools in The Channels, under low-flow conditions, were most likely to have been produced by phytoplankton blooms or dense benthic microbial mats. Although the presence of phytoplankton and microbial mats can be established from aerial photography, accompanying field surveys are needed to determine species composition.

The presence of clear, macrophyte-dominated regimes was not easily determined from the aerial photography available; however, the field visit made to Ossig's Lake in May 2004 revealed the presence of extensive dead mats of *Lamprothamnium* sp. and some live material. This suggested that conditions were suitable for the development of a clear, macrophyte-dominated regime in at least some of the lakes within the system. Stands of macrophytes provide a direct source of food for herbivores such as swans and habitat for invertebrates which, in turn, provide food for ducks and waders.

Conceptual model of the interaction between hydrology, geomorphology, and ecology in the Yenyening Lakes and salt river system

The complex pattern of lunettes, linear banks, mounds, and shallow channels present within the Yenyening Lakes system suggests that the retention time of water within the system is likely to be high under low to moderate flows. The exception would be the infrequent, episodic, very high flows such as those recorded in January 2000. The highly seasonal climatic regime of the region (cool, wet winters and hot, dry summers) also indicates that most of the shallow lakes would undergo extensive summer drying in low and average rainfall years. However, the present complex drainage network ensures that lakes dry to differing degrees, as indicated by different water levels in different lakes induced by retentiveness. Thus the present drainage network maintains a major degree of physical and ecological diversity even in its degraded state.

The high retention times produced by the complex within-lake and channel geomorphologies combined with shallow, seasonal water regimes indicate that conditions are likely to be suitable for high rates of benthic and water column primary production in these systems. Prior to the land clearing associated with European settlement, this system would have supported a rich freshwater ecosystem probably dominated by submerged aquatics. This system would have supported the prolific birdlife of ducks and swans described by the early explorers (Cross, 1833). The increase in salinity, water depths, and nutrients that accompanied clearing and subsequent cropping would have moved the aquatic system in the direction of dominance by phytoplankton or benthic mats. However, the presence of submerged aquatics at Ossig's Lake indicates that the salinity levels and water regimes are not so disrupted that an irreversible shift in ecological regime has occurred. Although it is unlikely that these waterbodies will ever be restored to a fresher state, their current diversity needs to be recognized and protected.

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Cross-references

[Aral Sea](#)
[Classification of Lakes from Hydrological Function](#)
[Dead Sea](#)
[Myponga Reservoir, South Australia: The Influence of Nutrients, Phytoplankton, Pathogens, and Organic Carbon on Water Quality](#)
[Poopó Lake, Bolivia](#)
[Water Balance of Lakes](#)

POOPÓ LAKE, BOLIVIA

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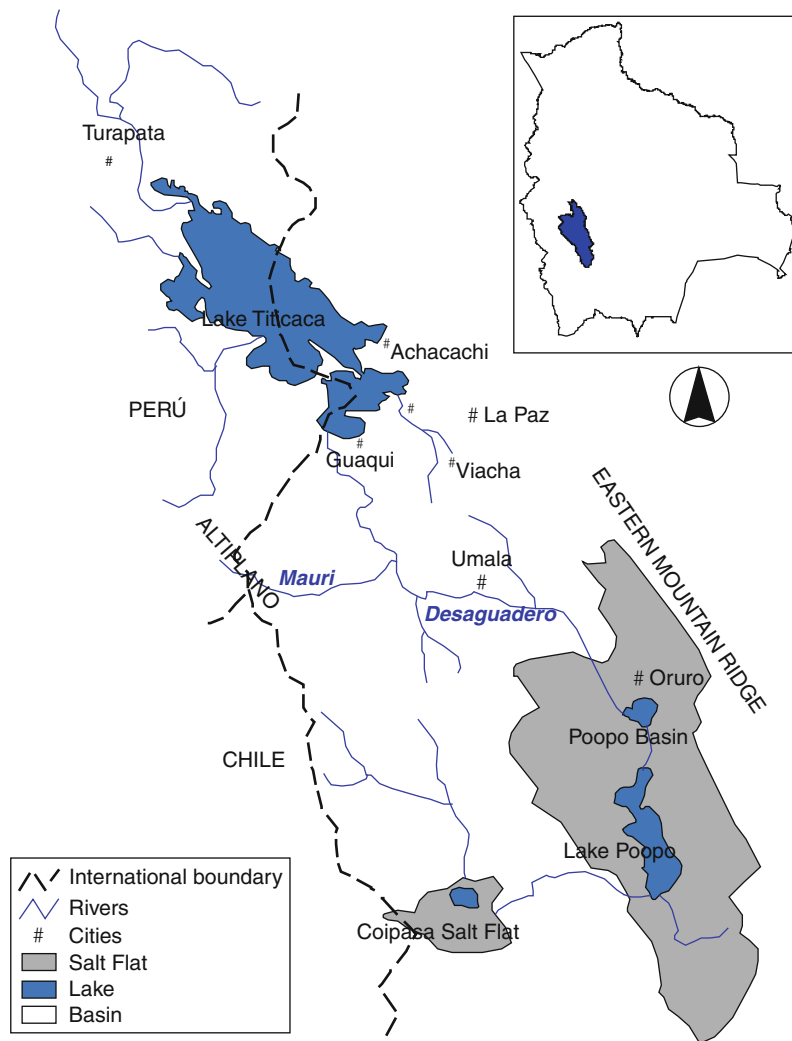
Description

Lake Poopó is located on the Bolivian high plains at 3,700 m above the sea level. The lake is part of the TDPS system (Lake Titicaca, the Desaguadero River, Lake Poopó, and the Salares (Salt Flats), [Figure 1](#)) forming an extensive endorheic basin. Lake Titicaca is the highest situated of the world's large lakes. The Desaguadero River links Lake Titicaca with the downstream Lake Poopó. Lake Poopó is an extremely shallow lake with a mean depth of less than 2 m below the outlet sill level. At spill-over level the lake surface is very large and exceeds 3,000 km². However, since it is so shallow, the lake may in very dry periods dry out. In the present-day climate, there is very seldom any outflow from the lake, which means that the water level and thus the surface area are highly variable. The lake is in principle a terminal lake. The water is salty. The character of the lake is illustrated in [Figure 2](#), which shows the flat shores.

Next to Lake Poopó is also Lake Uru-Uru. The Desaguadero River divides into two river arms, one branch into Lake Poopó and another into Lake Uru-Uru. Lake Uru-Uru spills over into Lake Poopó. Lake Uru-Uru dries out every year. Its maximum depth is 1 m, when the surface area is 300–400 km². Prior to 1985 the Desaguadero River ran through Lake Uru-Uru before entering into Lake Poopó itself. At high water levels the two lakes constitute one single lake.

The Salinas, two huge salt accumulations from old lakes, Salar de Coipasa and Salar de Uyuni, are south of and downstream Lake Poopó. Enormous changes have taken place of the hydrology of the Bolivian Altiplano. Several lacustrine layers have been found in the sediments from the Salares. During the Tauca period (26,000–15,000 BP), the lower part of the Altiplano constituted a large single lake basin, Lake Tauca. In a drier climate this lake developed into three lake basins, Lake Poopó and the two Salinas, of which today the Salinas are salt accumulations.

Today Lake Poopó can be considered to be a closed lake rarely having any outflow. Last time there was outflow from the lake was in the mid 1980s. In early 2001 the lake almost reached its sill level. The lake seems to have been dry between 1939 and 1944 and almost dry in the early 1970s and again in 1994–1996. In a normal year the lake area varies between about 2,000 km² in March at the end of the wet period and 1,000 km² in November at the end of the dry period. The variation of the lake surface area over 50 years is shown in [Figure 3](#). As can be seen, there is a close relation to the water level of Lake Titicaca.



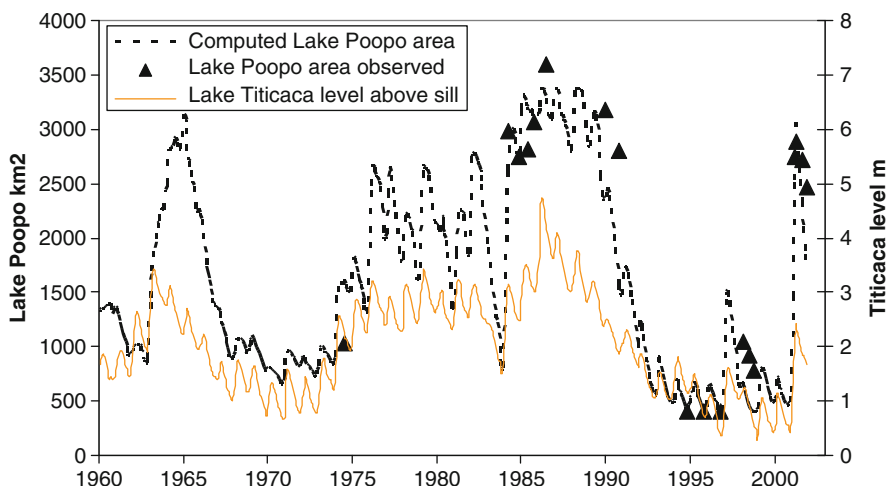
Poopó Lake, Bolivia, Figure 1 The Titicaca-Desaguadero-Poopó-Salares (TDPS) system on the Bolivian High Plateau (From Pillco Zolá, 2007).



Poopó Lake, Bolivia, Figure 2 The shores of Lake Poopó (Photo Lars Bengtsson).

Also since the lake is a terminal lake, it means that not only salt but all sorts of pollutants are trapped in the lake. On the mountain slopes at the eastern side of Lake Poopó, mine activities have been going on for centuries. There are leakage of water very high in heavy metals from mining ponds and even more leakage from abandoned old mines. The high content of metals is visible from the color of the water and the sediments in some of the small rivers flowing into Lake Poopó. In spite of poor environmental conditions, indigenous poor people living on the lake shores still get their income from fishing.

The water balance of Lake Poopó is much determined by the Desaguadero River flow. The flow from this river constitutes almost 70% of the water input to the lake, while the contribution from regional rivers is only



Poopó Lake, Bolivia, Figure 3 Computed and observed (from satellite images and water stage) lake area of Lake Poopó (Drawn from data presented by Pillco and Bengtsson, 2006a).

10–15%. Precipitation on the lakes, 370 mm per year nonuniformly distributed, is about 20% of the water input. The water loss from evaporation is about 1,800 mm.

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Cross-references

[Aral Sea](#)
[Hydrodynamics of Very Shallow Lakes](#)
[Playa Lake Chains: The Example of the Yenening Lakes of the Upper Avon River Catchment of Western Australia](#)
[Titicaca Lake](#)
[South America, Lakes Review](#)
[Water Balance of Lakes](#)

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RESERVOIR AND LAKE TRAP EFFICIENCY

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Introduction

All streams transport sediment, and some of this sediment will be deposited in the relatively quieter waters of lakes and reservoirs (Morris and Fan, 1997). This accumulated sediment is detrimental to the lake or reservoir because it displaces the storage of water and often reduces the surface area. It is especially problematic in reservoirs designed for hydropower production: as useful storage volume is lost, increasingly only the flow of the river is available, and this may be insufficient during low-flow periods. In areas of extremely high sediment yields, smaller lakes and reservoirs may fill completely, but this is relatively rare. For some regions, reservoir sedimentation is no longer seen as a major problem. Indeed, in the USA, reservoir sedimentation surveys are now rarely performed.

Basic processes

As the sediment-laden stream flows into the relatively quiescent pool, the coarser particles are more rapidly deposited, while the finer particles are transported farther into the reservoir depending on the velocity and dynamics of the water. In some cases, especially where there is a sub-crest outlet at the dam, a sediment-laden flow termed a turbidity current, made denser by the sediment or by thermal conditions, can transport fine sediment into the deeper portions of the pool and, on occasion, even through the sub-crest dam outlet. Indeed, some dams are designed and operated with this phenomenon in mind.

Sediment, and particularly coarse material, may also accumulate above normal pool level or crest level upstream of the reservoir or lake. This happens when the inflowing sediment forms a delta out into the pool. Because a stream must maintain a slope or gradient to furnish energy to flow, the slope must be extended upstream of the pool by aggrading or building up its bed with sediment. This process not only raises the elevation of the river but can also permanently flood the areas adjacent to the stream. Perhaps the most famous example is upstream of Elephant Butte Dam, completed in 1916 on the Rio Grande River in New Mexico. Located 2 km upstream of the reservoir pool and several meters above it, the small town of San Marcial was partially flooded and eventually evacuated by the 1930s (Eakin and Brown, 1939). This above-crest sediment creates a wedge and may extend many kilometers upstream.

The trapping of sediment by reservoirs and lakes can create a sediment deficiency downstream. That is, stream flow deprived of its normal sediment load becomes “hungry” and tends to erode available sediment in streambeds downstream of the dam. In some cases, streams have cut vertically or “degraded” several meters over reaches up to several kilometers downstream of dams, often destabilizing banks and leaving water intakes stranded above water level (Williams and Wolman, 1984).

While most perceive reservoir and lake sedimentation in negative terms, there are also positive aspects. One of these is that with at least part of the sediment having been removed, the water available at the downstream end of the pool may be clearer. Another advantage is that an opportunity is provided to measure sediment yield. The conventional way of measuring sediment in stream by sampling is a very imprecise and problematic process. This is (a) because much of the sediment load is carried near the streambed and often goes unsampled, a very serious problem in some streams, and (b) the stream must be sampled

over long periods of time, a difficult and expensive undertaking. Thus, the importance of pools is due to the fact that they (1) intercept all events, not just the ones convenient to measure and (2) intercept bedload, the portion of sediment yield normally not measured. Thus, lakes and reservoirs have the potential to give much more realistic measurements of sediment yields of streams. Such measurements have been used to estimate sediment yield and fluvial processes over historical periods (e.g., Trimble and Carey, 1990; Butcher et al., 1992; McManus and Duck, 1993; Dearing et al., 1990; Foster, 1995; White et al., 1996).

Trap efficiency

Not all of the sediment transported by the stream is trapped because much can be transported over and through the dam (Verstreten and Poesen, 2000). The proportion of stream load trapped over any time period is termed trap efficiency (TE) and is a function of the kinetic energy within the reservoir and the type of sediment. Heinemann (1981) stated that TE is the single most informative attribute of a reservoir. The TE is important because, assuming the mean sediment yield (SY) is known, it allows planning for the longevity of the lake or reservoir. And with measurements of the sediment accumulation over time, SY may be estimated by adjusting the accumulation by the trap efficiency. Thus, if the measured accumulation is 1,000 t/year and the TE is 50%, the SY is actually 2,000 t/year. Normally, mean SY is expressed as tons per unit area (e.g., 50 t/ha/year), known as unit SY.

Long-term trap efficiency

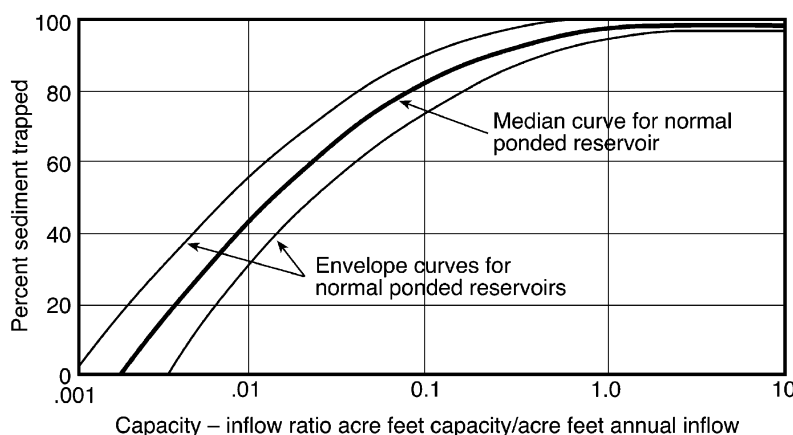
Since reservoirs are long-term investments, the long-term consequences of sedimentation have generally been of greater interest, and the same is true of sediment yields; thus, the development of long-term TE has been a priority. Additionally, the long-term data required have been systematically gathered since the early twentieth century, particularly in the USA. That is, many reservoirs were

given systematic hydrographic surveys which were repeated every few years, and compendia were published giving the results (e.g., Dendy and Champion, 1975). With the use of these data plus stream load data and empirical surrogates of kinetic energy in lakes and reservoirs, researchers sought to come up with reliable estimates of TE.

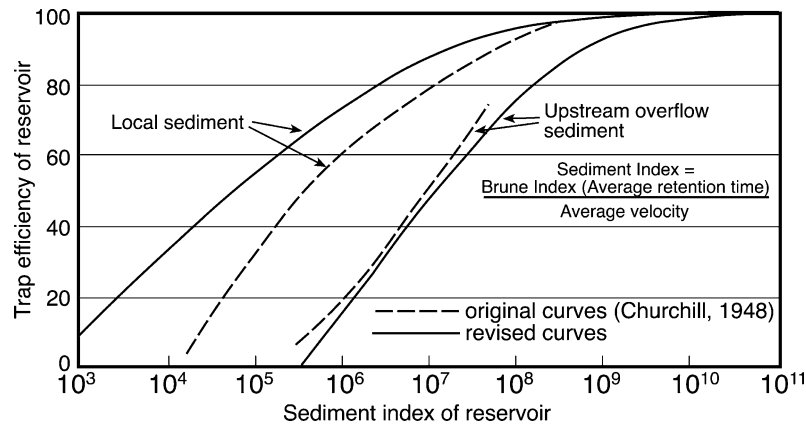
Brune model. One of the oldest and certainly the most used model is that of Brune who used data from 40 large, normally ponded reservoirs (1953, Figure 1). The independent variable or basic predictor is the ratio of pool capacity (volume, termed C) to volume of annual stream inflow (termed I). The C/I ratio is also called the period of retention because the number suggests the number of years. The pool dynamic here is annual turnover, with a C/I ratio of 1.00 meaning that the pool content theoretically is drained and refilled every year, the measure suggesting a relative measure of kinetic energy. The C/I ratio is also called the period of retention. Note that there is a median curve predicting TE for most common values of C/I, but it is flanked by curves more appropriate for coarser or finer sediment. Since C and I values are almost universally available and the model is very easy to understand and use, it has become by far the most commonly used model to predict TE (USDA-SCS, 1983).

The Brune model was devised using data from large reservoirs, and it was later found that it did not predict as well for smaller reservoirs and lakes. Thus, a similar model was devised for smaller reservoirs and ponds by Heinemann (1981) which has also found wide acceptance.

The Churchill model. As early as 1948, Churchill suggested a model much more sophisticated than the Brune model just discussed (Figure 2). Its independent variable or predictor was termed the *sedimentation index* defined as the period of retention (Brune's C/I index) divided by the mean flow velocity through the reservoir. Because very few measurements of the latter are available, the usual working definition is the average inflow volume divided by the average reservoir or pond cross-sectional



Reservoir and Lake Trap Efficiency, Figure 1 An updated version of the Brune model. From USDA-SCS 1983.



Reservoir and Lake Trap Efficiency, Figure 2 The Brune model with revisions by Trimble and Bube. (Redrawn from Trimble and Bube, 1990.)

area. In any case, the sedimentation index is a much better surrogate of kinetic energy in a reservoir than the Brune C/I index. The other strong suit of the Churchill model was that it distinguished between sediment produced within the local catchment (local sediment, presumed to be coarser) and that conveyed downstream through upstream reservoirs (overflow sediment, presumed to be finer). The problem with acceptance of the Churchill model was that it was based on only a few data points and that it appeared in a short discussion in a somewhat obscure source.

But some saw the potential in the Churchill model, and Borland revisited it in 1971 adding some data and giving the model more visibility. Bube and Trimble (1986) and Trimble and Carey (1990) refined the model and used it to advantage in comparative studies with the Brune model. Trimble and Bube (1990) used a very large data set (a cascading system of 27 reservoirs over about 40 years) to further refine the Churchill model (Figure 2). Sediment was cascaded through the system in a simulation, and variance was minimized to optimize the TE values for both local and overflow sediment.

Physically based approaches

Estimating the trap efficiencies of individual runoff events is important for ponds built to reduce sediment yield from construction and other land disturbing activities. Trap efficiencies obtained from long-term studies are often inadequate for this type of assessment. Physically based approaches are widely used to capture localized site and watershed characteristics. These approaches are also appropriate in computing the trap efficiencies of small lakes and reservoirs.

Physically based approaches are dependent on the influent sediment characteristics and on the hydraulic response and geometry characteristics of the reservoir. The most important characteristic of influent sediment is the particle size distribution. Large particles are obviously easier to trap than small ones. Inflow and outflow

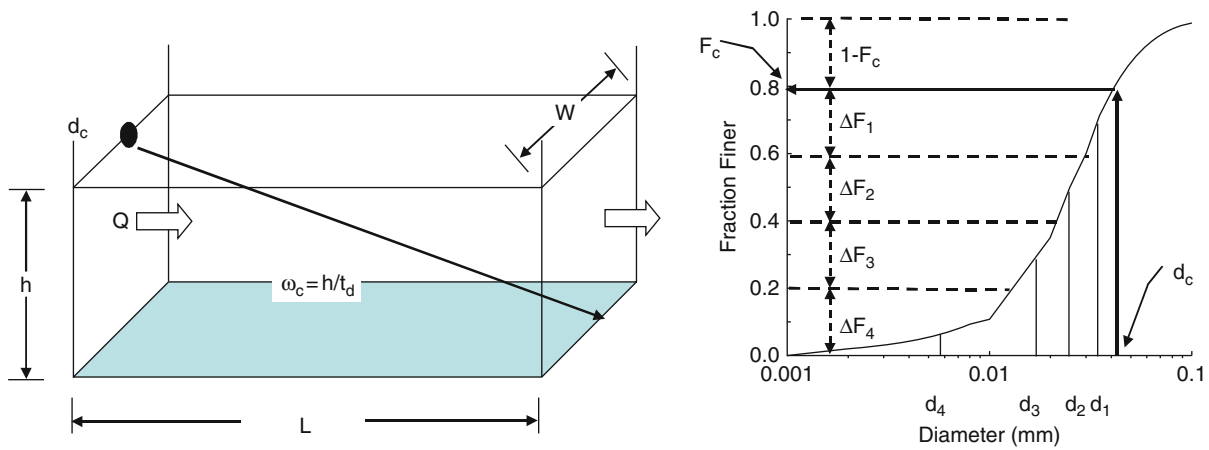
hydrographs are often used to estimate the hydraulic response of the reservoir. The outflow hydrograph can be computed using reservoir routing techniques (Haan et al., 1994). Although these techniques are straightforward, calculations can be tedious. Most physically based approaches are therefore computer programs that include reservoir routing computations as part of the analysis. Surface area as a function of elevation is an important relationship to characterize basin geometry and is necessary to perform reservoir routing. This relationship can also be used to estimate the fall distance for trapping of particles and, in more rigorous models, to determine hydraulic properties necessary for computing scour and turbulent characteristics.

Insight into the role of particle size, hydraulic response and basin geometry can be obtained by using overflow rate methods (Camp, 1946). Overflow rate methods were originally developed for sedimentation basins of wastewater treatment plants. Let's consider the idealized basin of constant depth shown in Figure 3. The idealized basin assumes steady flow with no mixing (plug flow assumption) among previous inflows, uniform vertical distribution of sediment at the inlet, no turbulence, and no resuspension of bed particles. There exists a particle diameter, d_c , that will fall the entire depth (h) within the time it takes to travel between the inlet and outlet. This time is called the detention time (t_d) and, for the idealized basin, corresponds to the time required to displace the basin volume (WLh) by the steady state flow (Q). The settling velocity (ω_c) corresponding to d_c is then defined as

$$\omega_c = \frac{h}{t_d} = \frac{Q}{A_s} \quad (1)$$

where A_s is the surface area of the basin (WL), and the detention time is obtained by dividing the volume by the flow rate.

The relationship of Q/A_s is called the overflow rate and is a function of basin hydraulics and geometry. By using Stokes equation or other settling velocity relationships,



Reservoir and Lake Trap Efficiency, Figure 3 Idealized basin for overflow rate methods.

the critical diameter corresponding to ω_c (as computed using Equation 1) can be computed (Haan et al., 1994). For the idealized basin of Figure 3, all particles larger than this diameter are trapped. The fraction of the total mass for these particles is defined from the particle size distribution. This concept is also shown in Figure 3 where “ $1 - F_c$ ” is the fraction of mass greater than d_c .

In addition to particles that settle the entire depth, smaller particles located closer to the bed will also be trapped. For the idealized rectangular basin, the trapping of these particles is proportional to the ratio of their settling velocities to the critical velocity. The overall trap efficiency of sediment using the overflow rate approach is then defined as

$$E = (1 - F_c) + \sum_{i=1}^n \left(\frac{\omega_i}{\omega_c} \right) \Delta F_i \quad (2)$$

$$= (1 - F_c) + \sum_{i=1}^n r_i \Delta F_i$$

where E is the trap efficiency, n is the number of class sizes of sediment with diameters (d_i) smaller than d_c , and ω_i and ΔF_i are the settling velocity and fraction of mass corresponding to d_i . A conceptual representation of the terms in Equation 2 is shown in Figure 3 for the case where $n = 4$. The ratio ω_i/ω_c is often called the Hazen number. For the idealized basin, it corresponds to the fraction of particles (r_i) of diameter d_i that are trapped.

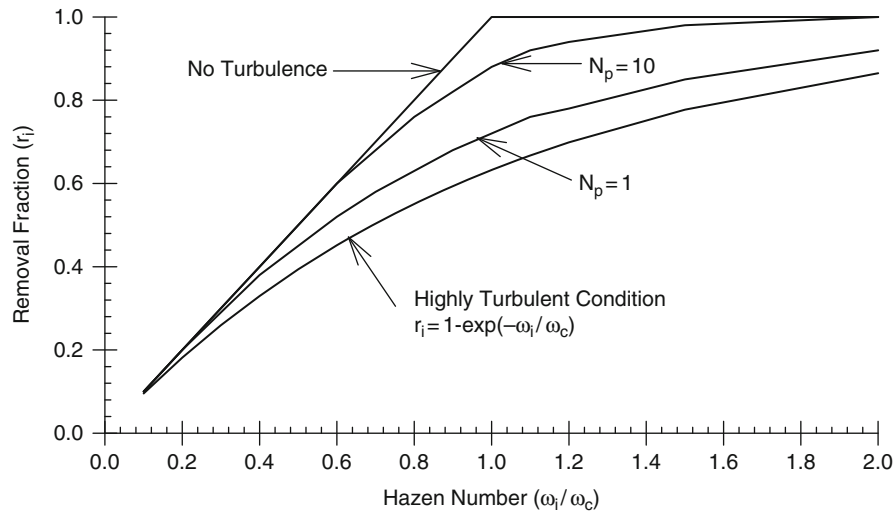
Extensions are needed to the overflow rate methods to predict trap efficiencies of irregularly shaped lakes and reservoirs with unsteady flows. However, before discussing these extensions, let's consider less restrictive conditions for the idealized basin of Figure 3. Detention time in Equation 1 is computed by displacing the entire basin volume with flow. Often a fraction of the basin volume is effectively isolated from the flow patterns. This isolated volume is called dead space. Camp's trap efficiency approach is easily modified for dead space by

simply decreasing the detention time to correspond to a smaller volume displaced by flow. The revised detention time is simply computed as $WLh(1 - f_d)/Q$, where f_d is the fraction of dead space.

Since some mixing of flows occurs within the basin, much research has been done to remove the assumption of plug flow. Simple reactor models provide a framework for representing non-plug flow characteristics. Reactor models are developed by dividing the basin into chambers or reactors in which either plug flow or completely mixed flow can occur (Wolf and Resnick, 1963; Cooper and Jefferys, 1971). Separate mass balances are used for each reactor. The level of mixing can be controlled by increasing or decreasing the number of reactors. Plug flow corresponds to the special case of an infinite number of reactors. Chemical dyes can be used to determine the appropriate reactor configuration. Griffin et al. (1985) provide results that can be used to estimate the number of completely mixed reactors and the fraction of dead space for lake and small reservoirs.

The impact of turbulence on the trapping of particles was investigated by Dobbins and Camp as early as 1944. Dobbins solved a mass balance for one-dimensional flow in rectangular basin using a turbulent diffusion coefficient that is independent of depth. His solution is a function of the previously given Hazen number (i.e., ω_i/ω_c) and the sedimentation Peclet number. The sedimentation Peclet number is a measure of the relative movement of sediment by settling to that by turbulent diffusion. Hence, large Peclet numbers correspond to conditions where the relative movement of sediment by turbulence is small.

The impact of turbulence on the removal fraction of particles of size d_i (r_i) is shown in Figure 4. The solution for r_i with no turbulence, as originally formulated in Equation 2, is given by the one-to-one line in this figure. As turbulence increases, the Peclet number decreases, and the removal fraction of particles also decreases. For example, all particles are trapped for Hazen number of one with no turbulence. The removal fraction is reduced



Reservoir and Lake Trap Efficiency, Figure 4 Impact of turbulence on trapping of particles.

to roughly 0.9 and 0.7 for Peclet number of 10 and 1, respectively. The exponential relationship for r_i proposed by Chen (1975) for highly turbulent conditions corresponds closely to the solution of a Peclet number of one tenth. As shown by Figure 4, all particles are no longer trapped for diameters greater than d_c with turbulence. Therefore, the “ $1-F_c$ ” term in the trap efficiency given by Equation 2 is no longer appropriate. Equation 2 is easily modified for turbulence by removing “ $1-F_c$ ” and by including additional diameters greater than d_c in the summation term (Haan et al., 1994).

As an alternative to reactor models, hydraulic flow characteristics can also be predicted using basic hydrodynamic relationships. Here the movement of fluid and sediment is predicted by coupling conservation of mass relationships with an equation(s) of motion. An important theoretical challenge with this approach is the representation of fine time and length scales necessary to represent turbulence. Time or space averaging techniques are therefore used, but these techniques introduce additional stress terms (Pope, 2000). Although the determination of constitutive relationships for these stress terms has received much attention, more work is needed for the complex flow patterns in lakes and reservoirs. Hydrodynamic relationships can be formulated for three-dimensional problems. Two-dimensional depth-averaged solutions have also been proposed to reduce computational requirements (Rastogi and Rodi, 1978).

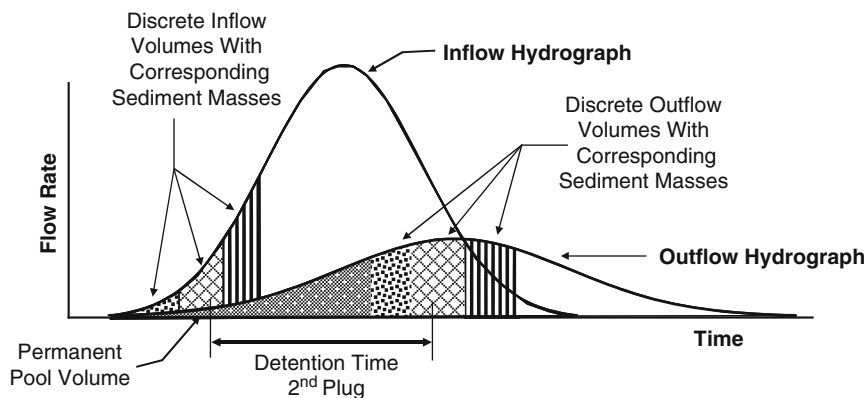
Physically based models

The overflow rate concepts of the previous section have been modified to predict trap efficiencies of irregularly shaped lakes and reservoirs. A simple approach is the EPA method (see Haan et al., 1994) where the flow rate is defined using the peak outflow rate and the surface area is defined as that area corresponding to the crest of the outlet riser. The overflow rate is increased by a factor of 1.2 to

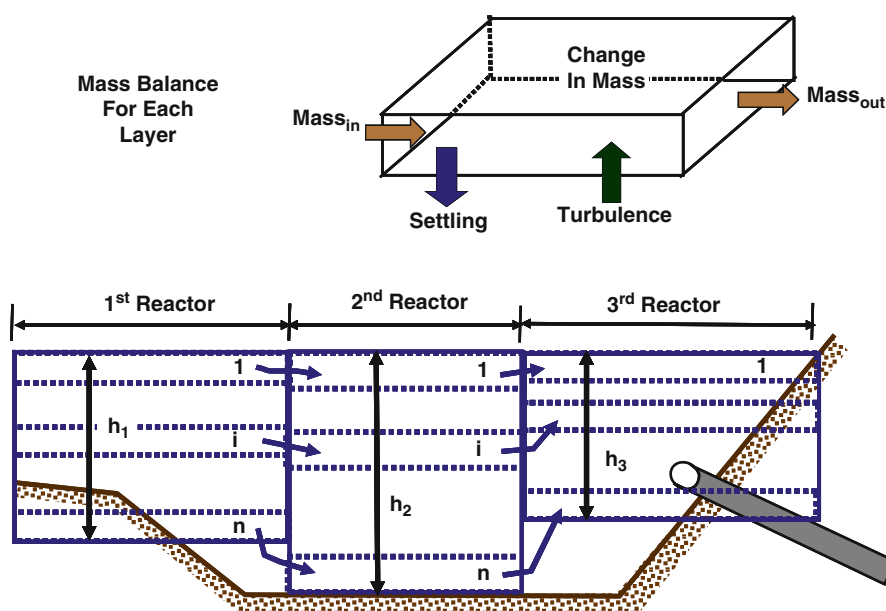
account for nonideal characteristics. This overflow rate is assumed to be constant for all inflows. Tapp et al. (1981) extended the EPA method to vary the overflow rate with time. They proposed two methods. One method uses time-varying outflows to compute overflow rates; the other method uses both outflows and fall depths to determine time-varying overflow rates. These simple extensions are, at best, modestly effective. They oversimplify complex processes.

Ward et al. (1977, 1979) developed a comprehensive pond simulation model called DEPOSITS (Detention Performance Of Sediment In Trap Structures). The DEPOSITS model assumes plug flow. However, in contrast to the overflow rate methods, the critical settling velocity is obtained directly from the fall depth-detention time ratio of Equation 1 (i.e., h/t_d) and not the overflow rate itself. A detention time is computed for each inflow plug entering the reservoir or lake. The time corresponding to the discharge of the plug is computed from a cumulative outflow volume curve. This concept is shown in Figure 5. The first inflow plug is the first outflow plug discharged after the permanent pool is “pushed” out of the basin. The average fall distance for particles is computed using a volume-weighted depth corresponding to the time that the sediment is in the reservoir or lake. The DEPOSITS model has been shown to have good accuracy in predicting observed trap efficiencies, but can have problems in predicting the observed effluent concentrations (Ward et al., 1977, 1981; Wilson and Barfield, 1981).

The inability of the DEPOSITS model to predict accurately observed effluent concentrations is likely caused by the limitations of assuming plug flow. To allow mixing between inflows and the permanent pool volume, while maintaining a relatively simple computational framework, Wilson and Barfield (1984) developed the CSTRS model. With this model, the reservoir is divided into reactors or



Reservoir and Lake Trap Efficiency, Figure 5 Computation of detention time for plug flow models with unsteady flow.



Reservoir and Lake Trap Efficiency, Figure 6 Representation of flow processes in the BASIN model.

chambers of equal volume. A mass balance is then maintained for each reactor. A critically important component of this mass balance is the deposition within a time step. In contrast to the plug flow model of DEPOSITS, where a single detention time can be used for each inflow volume shown in Figure 5, the sediment in the CSTRS model mixes with other sediment from previous inflows and, therefore, cannot be represented by a single detention time. Some particles remain in the reservoir for a long time, whereas others are discharged almost immediately. This variation in residence time is estimated using idealized deposition processes in the reservoir and identifying simple trends of depositional patterns with time. A comparison of predicted and observed results with the DEPOSITS and CSTRS model showed relatively small differences in trap efficiencies (Wilson and Barfield, 1984). However, the CSTRS model was superior in

predicting the observed effluent concentrations. The DEPOSITS and CSTRS models are both options in the SEDIMOT II (Wilson et al., 1984) and SEDCAD (Schwab and Warner, 1996) watershed models for computing trap efficiencies in small reservoirs.

Although the CSTRS model is an improvement in representing flows within reservoirs and lakes, it is still limited by not considering the impact of turbulence and bed scour and resuspension. The BASIN (Basin Analysis of Sediment-laden INflow) model was developed by Wilson and Barfield (1985) to account for these processes in the prediction of trap efficiencies. The BASIN model also divides the ponds into a number of reactors. By assuming mixing within the reactor in only the non-vertical directions, a sediment balance can be easily derived for infinitesimally layer, as shown in Figure 6. This sediment balance is then solved using an efficient

numerical algorithm. Turbulent diffusion coefficients are required to simulate the impact of turbulence. Bed scour calculations are required to establish the lower boundary condition. Oolman and Wilson (2003) modified the BASIN model to allow the turbulent diffusion coefficient to predict directly in the model using the theory presented by Wilson and Barfield (1986) and to utilize the detachment algorithm developed by Wilson (1993).

Hydrodynamics models are the most rigorous approach to represent flow processes in lakes and small reservoirs. Kersten (1963) used jet theory to represent the hydraulic characteristics of flow at the reservoir's inlet and then solved the mass balance equation for sediment using finite difference techniques. Kuo (1976) further expanded upon this work by assuming the flow is symmetrical between the inlet and outlet. Chen et al. (1978) used a depth-averaged form of the mass balance for sediment and water and an equation of motion. The reservoir is divided into "subchannels," and lateral flow is used to have flow between these subchannels. More recently, Kennedy et al. (2006) used a three-dimensional hydrodynamic model to determine the hydraulic retention time of flows in reservoir. A tetrahedral mesh of more than 1.6 million cells was used to represent the basin bathymetry and inlet and outlet conditions.

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Cross-references

[Reservoir Sedimentation](#)
[Sediments, Flushing from Reservoirs](#)
[Turbidity Currents in Reservoirs](#)

RESERVOIR CAPACITY

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Introduction

During high river flows, water has to be stored so that a uniform supply of water can be assured for supply for drinking, irrigation, power generation, and other needs during periods of low river flows.

Hydrological investigations are necessary for the design of a reservoir in consideration of the following:

1. Quantity of water available
2. Quality of the source
3. Construction
4. Suitability of the dam
5. Distance from the source to the customer
6. Elevation of the reservoir
7. Safeguard of quality
8. Topographic survey
9. Geological survey
10. Appraisal of necessary land use
11. Cost of the scheme

The estimation of the quantity of water which the reservoir will yield is the first consideration, and it is necessary to make estimates of the yield in relation to the amount of storage and capacity the reservoir will hold. The yield of a reservoir is the volume of water regularly available over a unit period of time.

Methods used for estimating capacity

The following methods may be used for estimating capacity: (1) the graphical method and (2) the numerical method.

1. Graphical method

Figure 1 shows an example of a mass curve to determine the storage capacity of a reservoir. Plots of the cumulative sums I and D represent the inflow and outflow draft mass curves, respectively, with S the initial reservoir storage. It can be seen that the reservoir storage capacity is the difference between the input and output mass curves. In Figure 1 the reservoir storage S is determined for a constant draft D with the constraint that no failure is allowed during the design period. The procedure employs the concept of a semi-infinite (bottomless) reservoir and yields the required storage capacity as the minimum storage depletion recorded in an initially full reservoir during the design period. The constant draft corresponds to a constant slope of the draft mass curve D. A line parallel to D is drawn through each peak on the inflow mass curve I. The design storage capacity S is the maximum vertical distance between any point on I and any of the lines that are parallel to D.

2. Numerical method

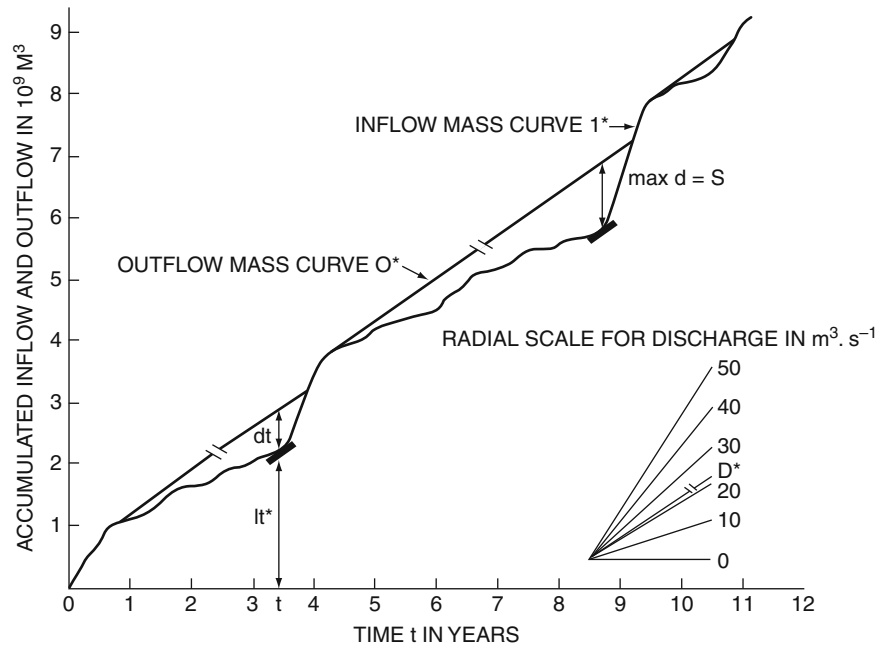
The numerical method for the estimate of storage is a mass balance between water entering a reservoir (precipitation, streamflow). The equation is:

$$S_i = S_{i-1} + I_i + P_i - E_i - D_i - O_i \\ = S_{i-1} + \Delta S_i \quad (1)$$

where S_i is the storage capacity at the end of time interval i , S_{i-1} is the storage at the beginning of time interval i , I_i is the inflow during interval i , E_i is the evaporation during interval i , D_i is the draft or abstraction during interval i , O_i is the outflow or spillage during interval i , and ΔS_i is the change in storage during interval i .

Other computerized methods that aid computation analysis are available especially in the design and operation of multipurpose reservoirs requiring complex analysis normally carried out by iterative methods.

Where storage needs to be determined to maintain a certain draft, Equation (1) is solved for different assumed maximum storage capacities (S) to find, in an iterative manner, the capacity where the reservoir is drawn down to almost empty, or the minimum operating level. Where a dam already exists or the storage is fixed, the abstraction rate which can be maintained can be determined by



Reservoir Capacity, Figure 1 Mass curve approach for the determination of storage capacity S required for supplying constant draft D (Note: This figure is reproduced with the kind permission of WMO).

substituting storage with draft as the variable in the equation. The sequence of levels of reservoir storage which result from solving Equation 1 is referred to as the storage trajectory.

The trajectory will generally be bounded by the full and minimum operating level states. In general, the trajectory for a given inflow sequence and abstraction rate will be a function of the starting storage level and will differ from starting level to starting level. However, once corresponding full or minimum operating level states have been reached for the range of starting storages, the trajectories from that point onward will be indistinguishable for a given inflow sequence and abstraction rate.

The period of maximum drawdown of a reservoir, that is, from a full state of storage down to the minimum operating level and recovering until it reaches the full level again, is referred to as the critical period. To reach stability in the analyses, it is important that the critical period be clearly defined by the reservoir trajectory.

Computing power has increased significantly, facilitating the solution to Equation 1, and reservoir design has been improved by the digital approach, offering greater flexibility in analyzing various scenarios of the storage-yield relation.

Remote sensing estimates of reservoir capacity

Digital multispectral data can be used for delineation of surface water bodies including lakes, reservoirs, and ponds. These data can be subjected to automated analysis and meet accuracy requirements. Satellite data provide to determine morphometric parameters such as length,

width, and surface area for different elevations depending on the satellite resolution.

From a remote sensing perspective, water has a low reflectance especially in both the near-infrared and visible portions of the electromagnetic spectrum. Remote sensing can really only determine the surface of the water and not measure volume of water in storage directly in reservoirs. For this purpose a relation between reservoir water stage and volume is prepared.

Climate change and its effect on storage

There is evidence that global temperatures are rising, and the rate of increase may be significantly higher than has occurred in the past. Models suggest that this could cause change in precipitation and increase the variability of climate, and streamflow could decrease by the year 2015.

Such changes would have significant impacts on yield and on the water resource systems.

In storage design scenarios, it is appropriate to consider any impact of climate change during the life of the reservoir.

The effect of floods on storage

The storage to be provided to retain flood waters in a reservoir depends on the volume, peak flow, and expected duration of the flood. Because floods may occur at any time during a season, reservoirs may have to be designed to have a storage capacity to allow for floods and can sometimes be designed as either onstream or off-stream reservoirs.

Flood detention storage is often provided in multipurpose onstream reservoirs with a facility to provide a high degree of control.

In multipurpose reservoirs, storage has often to make provision for other interests such as irrigation and hydro-power as well as flood control, and sometimes these interests compete with each other. This is especially the case when more than one country is involved.

The storage required in multipurpose reservoirs, therefore, requires a compromise to realize the maximum benefits.

The effect of drought on storage

In studying yield of a catchment, the variability of runoff is considered, and, in this case, yield may be defined as the uniform rate at which water can be drawn from the reservoir throughout a dry period of specific severity without depleting the contents to such an extent that withdrawal at the rate is no longer feasible. So given a fixed storage capacity in the reservoir, over a drought period of greater severity than that of the design, the regular amount of water available for supply, yield would have to be reduced. The occurrence of any such drought governs the yield for a given storage. Alternatively, if a constant yield is required beyond the capabilities of a reservoir designed to fulfill requirements over a drought of specified severity and duration, the capacity of the storage would need to be increased to meet the demand. To ensure adequate storage for a constant yield or to evaluate the yield of an existing reservoir, the study of low river flows is crucial.

Computing power has increased significantly, facilitating the solution to [equation \(1\)](#), and reservoir design has been improved by the digital approach, offering greater flexibility in analyzing various scenarios of the storage-yield relation.

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Cross-references

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RESERVOIR SEDIMENTATION

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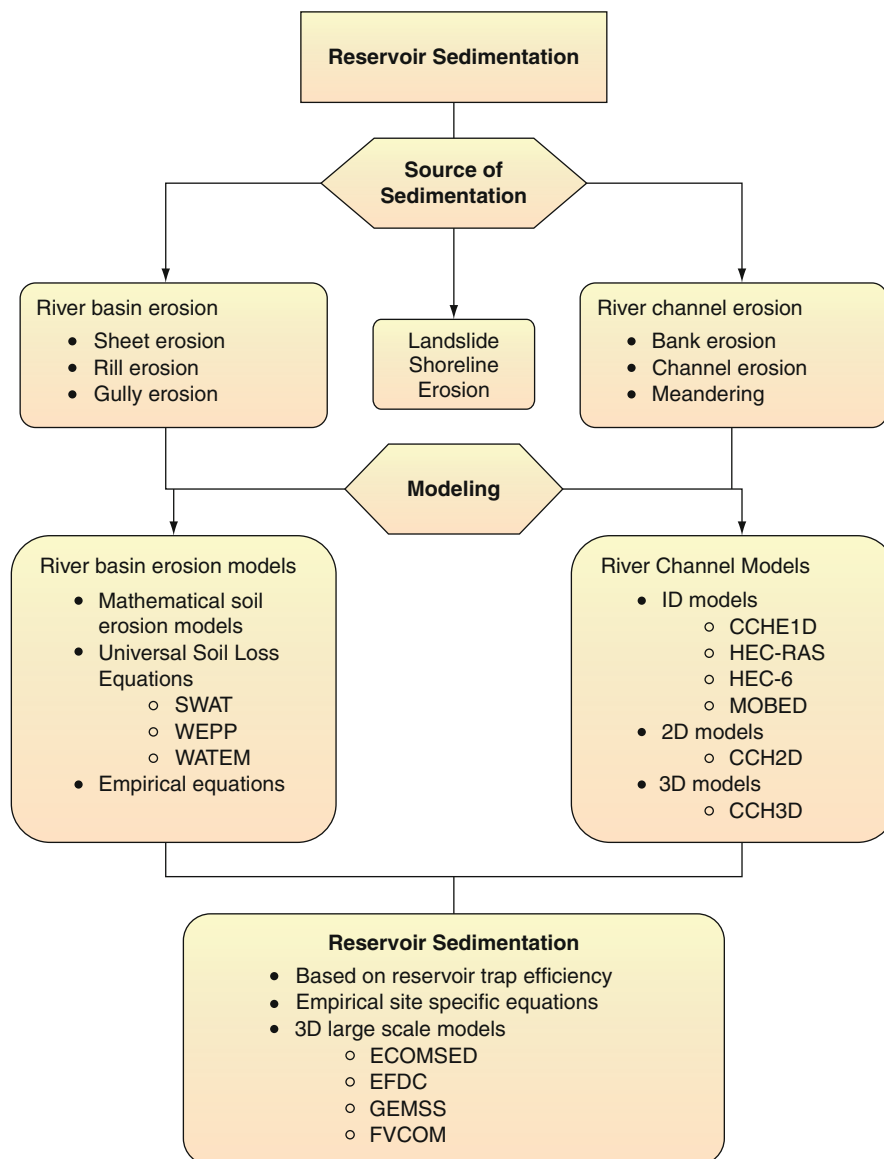
Introduction

Reservoir sedimentation is the gradual accumulation of the incoming sediment load from a river. This accumulation is a serious problem in many parts of the world and has severe consequences for water management, flood control, and production of energy. The worldwide loss in reservoir storage capacity is reported to be between 0.5% and 1.0% per annum (White, 2000). The gradual process of sedimentation proceeds with different speeds that depend on a large number of factors, such as hydrology of the catchments and the characteristics of the river basin. Sediment will eventually fill a reservoir within 50–200 years. Here, the crucial point is the fact that reservoir sedimentation is just a symptom of erosion of the topsoil. The principal causes are anthropogenic activities such as deforestation, and overgrazing. The complexity of the problem increases when the anthropogenic activities interact with natural changes imposed by the dynamic nature of climate and the earth surface processes. It is reported that 30% of the world's arable land has become unproductive during the past 40 years (Center for Earth Leadership, 2010). The same source reports that 65% of the earth's top soils are already degraded. An intriguing article published by *National Geographic* in the September 2008 issue (Mann, 2008) explores different aspects of soil erosion and the role of traditional methods for its mitigation. Mann states that only 3% of the earth's surface can be cultivated in soils

that are only 20 cm thick. The exception is the very limited regions of terra preta, or “black earth,” mainly found in Brazil’s Amazon Basin where the soil thickness is about 2 m. The point here is to emphasize two important aspects. One of the starting points for understanding and analyzing reservoir sedimentations is the understanding of soil erosion. Second, a mitigation plan is only effective if it includes soil conservation measures. Achievement of the task requires careful consideration of three interrelated areas:

1. The source of sedimentation and the processes involved
2. Modeling of erosion and sedimentation processes
3. Mitigation measures and their effectiveness

Figure 1 shows a general schematized chart of reservoir sedimentation sources and different modeling approaches. The source of reservoir sedimentation should be seen in relation to its cause. Here, it is instructive to consider the available lessons on the reasons for sedimentation of reservoirs. An important reason appears to be the failure in considering the reservoir as an integrated part of the river basin (Chanson and James, 1998). Bowonder et al. (1985) gave a number of specific reasons for sedimentation in reservoirs in India. Among these are land use policy, the absence of land use regulations, poor monitoring systems, lack of awareness of soil erosion and the value of soil conservation measures, emphasis on short-term gains, poor coordination of activities, and the lack of a trained



Reservoir Sedimentation, Figure 1 A schematic of reservoir sedimentation source and modeling.

workforce. The author recognizes the socioeconomic aspects as a central issue that probably would apply to many regions in the world.

Sediment is often both dissolved and solid with non-cohesive and cohesive properties. Dissolved loads are products of chemical weathering, and solid loads are delivered from the basins into the rivers through the action of rock weathering (Nichols, 2009). The quantity and type of sediment depend on the geology, topographic character, climate, vegetation type, and land use within the drainage basin. Sediment yield worldwide varies from one to more than 1,000 t/km²/year. In the lower range are desert regions and in the upper range are large mountain belts (Jansson, 1988). Extreme high yields in the range 10,000–50,000 are reported for basins in China, Java, Kenya, New Guinea, and New Zealand (Walling, 1994).

The subject of reservoir sedimentation has been thoroughly investigated and researched. The author has located over 350 journal papers among which are several useful handbooks and guidelines that deal with general sedimentation aspects, sediment yield, and mitigation methods. Some of main contributions are as follows:

1. An extensive review of methods to compute reservoir sedimentation is given by Bruk (1985) on the initiatives of UNESCO. The review is particularly interesting as many case studies as well as practical applications are included.
2. Morris and Fan (1997) give a comprehensive treatment of the subject area in a handbook of reservoir sedimentation. The US Army Corps of Engineers (1997) published a short summary of hydrological requirements for reservoirs. The manual was intended to serve as guidance to field office personnel for hydrologic engineering investigations for the planning and design of reservoir projects.
3. The details of the sedimentation processes and their control are summarized in a manual of reservoir silting and desilting (Batuca and Jordaan, 2000).
4. Xiaoqing's manual (2003) on sediment management provides a comprehensive revision of different aspects of sediment transport and its management. Ecological and environmental aspects are highlighted. Useful methods are outlined for computing soil erosion and sediment transport in rivers. A set of empirical equations are listed for estimating reservoir sedimentation characteristics.
5. On the initiative of the World Bank, a computer model RESCON 2003 (REServoir CONservation) was developed for the economic evaluation of sediment management. The key algorithm of the model is an economic optimization function that helps to quantify basic parameters. The model can be used to assess the technical and economic feasibility of implementing the life cycle management approach development.
6. A practical design manual, published by HR Wallingford as a guideline for predicting and minimizing sedimentation in small dams (DFID, 2004), provides useful procedures for predicting soil erosion, sediment yield, and the sedimentation rate in small reservoirs. The manual includes several worked examples that serve to illustrate the methods to the reader.
7. A large number of excellent articles are assembled in a technical document published by UNESCO in its Hydrology Series (Summer and Walling, 2002). The articles address various issues in modeling erosion. The document also includes two valuable sections on the comparison of different erosion and transport models.
8. Reservoir sedimentation, monitoring, and management were the theme of the sixth Federal Interagency Sedimentation Conferences. The proceeding was compiled in two volumes that included many topics on erosion control, river channel morphology, sediment transport, watersheds, and different modeling approaches (FISC, 2006).

Several interesting cases studies are also available that can serve as valuable sources of information (Atkinson, 1996; Morris and Fan, 1997; Chanson and James, 1998; de Oliveira Carvalho et al., 2000; Althaus and Cesare, 2006; Muller and Cesare, 2009).

River response to dam construction

Sediment is continuously supplied to rivers primarily through the process of surface erosion. Reservoir sedimentation is a fluvial process resulting from intercepting the natural flow of a river by constructing a dam or other wall structures. In their natural environment, rivers function as efficient conduits for transporting water and the supplied sediments composed of both dissolved loads and solid particles. Rivers constantly adapt themselves to a dynamic equilibrium regime through the action of the driving forces and adjustment of their morphological characteristics such as shape and orientation. The equilibrium regime prevails when the transport capacity for water and sediment are balanced with the supply rates. The construction of any barrier such as a dam distributes the natural dynamic status of the river. The kinetic energy of the river flow reduces as the river enters a reservoir. The process leads to reduced transport capacity of sediment in the river, thus causing gradual sedimentation. The sedimentation will take place both in the reservoir and at its upstream in the form of extensive river bed aggradation (sedimentation). The qualitative river response to the dam interception is illustrated using the relationship given by Lane (1955):

$$Q_s D = Q S \quad (1)$$

in which Q = water discharge, S = river slope, Q_s = sediment discharge, and D = the median sediment. Assuming the sediment size and the water discharge are kept constant, the increase in sediment discharge will be accompanied by an increase in the slope according to Equation 2:

$$Q_s^+ D^0 = Q^0 S^+ \quad (2)$$

Equation 2 shows that the river response is aggradation in the upstream channel. This is the backwater effect which results to M1 curve of gradually varied flow. Aggradation can spread to a considerable distance upstream of the dam after a long time and thereby increases the flood stage. The river may adopt a new channel in case of extensive aggradation in its channel. In an analogy to Equation 2, the river bed degradation (erosion) takes place downstream of the dam where the slope decreases due to decreased sediment load, i.e., $Q_s^- D^0 = Q^0 S^-$. The temporal bed profile variations can be estimated from the analytical solution to the Saint-Venant-Exner equations, i.e., Equation 3 (see Graf, 1998):

$$z(x, t) = \Delta h \operatorname{erf}\left(\frac{x}{2\sqrt{Kt}}\right), \quad K \cong \frac{1}{3} \xi q_s \frac{1}{(1-\lambda)S_e} \quad (3)$$

in which z is the bed level, Δh = thickness of the aggradation layer, x = distance, t = time, q_s = sediment load, ξ = coefficient for sediment gradation ≈ 5 (Graf, 1998), and S_e = energy line slope. Equation 3 is only applicable for $x > 3h/S_e$ (h = flow depth) and $Fr < 0.6$. Fr is the Froude number which is the ratio of flow velocity to the square root of acceleration of gravity times flow depth. The values of the error function erf can be obtained from a mathematical table (*Handbook of Mathematical Function* 1964). The length of deposition, L_d of $z/\Delta h = 0.01$ yields from Equation 3 as $L_d \approx 3.65 (Kt)^{0.5}$. Δh can be derived from Equation 3:

$$\Delta h(t) = \frac{\Delta q_s \Delta t}{1.13(1-\lambda)\sqrt{K\Delta t}} \quad (4)$$

in which Δt = time interval and Δq_s = sediment discharge at Δt . To illustrate the use of Equations 3 and 4, consider a river where river slope = 5×10^{-4} , sediment size = 0.32 mm, flow discharge = $1.5 \text{ m}^3/\text{s}$, $q_s = 1.7 \times 10^{-4} \text{ m}^2/\text{s}$, and $\lambda = 0.4$. After 50 h the aggradation thickness will be 0.06 m and its distance 1,500 m (Graf, 1998). The strength of the outlined method lies with its simplicity and applicability to both aggradation and degradation problems.

The right hand side of Equation 1 gives the river stream power when multiplied by ρg , i.e., $P = \rho g QS$, where ρ = density of water and g = acceleration of gravity (Lane et al., 1994). Stream power is an important concept in sediment transport that can be related to the total sediment transport (e.g., Bagnold, 1977) as well as the total sediment concentration (e.g., Yang and Molinas, 1982). The sediment rate G_s (kg/s) becomes proportional to P/D .

Sedimentation process

The sedimentation process in a reservoir is a result of a complex interaction between the various sediment transport processes that prevail in the river and the surface soil erosion as well as the hydrodynamics of the reservoir. To understand the sedimentation process, one must consider the process in three interrelated stages:

(1) the motion of sediment particles, (2) the process of soil erosion in the river basin, and (3) the river channel sediment transport characteristics. All these processes are controlled by a large number of flow parameters, soil or sediment properties, basin properties, and the hydrological variables.

Sediment particle motion

The motion of sediment particles is caused by the combined action of the gravity force working on the sediment particles and the entrainment of sediment particles by flow forces. The latter are the hydrodynamic forces that act upon the particle, producing drag and lift forces. The sediment particles will remain in an equilibrium state as long as the critical particle shear stress is not exceeded. Under increasing flow velocity, the magnitude of the flow forces will exceed the critical shear stress and the particles start to move. The critical shear stress (τ_{cr}) is commonly determined using the Shield (1936) diagram that relates the shear stress to the particle Reynolds number ($u_* D_m/\nu$). The relationship reads:

$$\frac{\tau_{cr}}{g(\rho_s - \rho)} = f\left(\frac{u_* D_m}{\nu}\right) \quad (5)$$

in which g = acceleration of gravity, ρ_s = sediment density, ρ = water density, u_* = shear velocity (hydrodynamic force), and D_m = characteristic sediment diameter. The critical shear stress can also be written in terms of critical shear velocity as ρu_{c*}^2 . Equation 5 is one of the most important relationships used in sediment transport. The left-hand side of the equation assumes a constant value 0.06 for Reynolds numbers greater than 500. Equation 5 only applies to non-cohesive sediment. The complexity of the problem increases with the cohesion of the material that is related to physicochemical forces. The dominant sediment type in most reservoirs ranges from silt to clay with high cohesion. There are no theoretical equations that can describe the motion of cohesive materials because the physical processes are not yet fully understood. The critical shear stress for cohesive particles (τ_{co}) can be estimated from Equation 6 (Lick, 2009):

$$\tau_{co} = \left(1 + \frac{ae^{b\rho_s}}{D_m}\right) \tau_{cr-n} \quad (6)$$

in which $a = 8.5 \times 10^{-16} \text{ m}^2$, $b = 9.07 \text{ cm}^3/\text{g}$, and τ_{cr-n} = critical shear stress of non-cohesive particles N/m^2 . Equation 6 shows that the critical shear stress increases significantly for cohesive particles. The increase is due to the attractive force between the particles. The other important physical parameter is the settling velocity of sediment particles as it is directly related to sedimentation in a reservoir. For a non-cohesive spherical particle, the settling velocity (known also as fall velocity) for Reynolds numbers greater than 1,000 is given by Equation 7 (Chien and Wan, 1999):

$$\omega = 1.72 \sqrt{\frac{\rho_s - \rho}{\rho}} gD \quad (7)$$

The approximate equation for cohesive particles less than 1 mm in diameter reads (Lick, 2009):

$$\omega = 0.268D_m^{1.56} \quad (8)$$

Equation 8 applies to sediment concentrations of 50, 100, and 200 mg/L. The settling velocity of cohesive particles is affected by sediment concentration, salinity, and flocculation (for details see Chien and Wan, 1999). Generally there is a logarithmic relation between settling velocity and sediment concentration. A critical concentration is found at 15 mg/L. The settling velocity increases sharply for values below the critical concentration, but it decreases for values above it. It is also found that the flocculation effect on settling velocity is important when the particle size is less than 0.01 mm. Under this condition the settling velocity increases with the flocculation factor. A fundamental consideration in reservoir sedimentation is the probability and the rate of sediment suspension. The ratio of the settling velocity to the flow shear velocity can be used to decide the probability of sediment suspension. Based on experimental observation, the ratio varies in the range 0.5–5.

One other important aspect that affects the forgoing discussion is the bulk density of sediments that depends on consolidation. An empirical relation is given by Lane and Koelzer (1953) for reservoir applications:

$$\rho_{bT} = \rho_{b1} + B \log T \quad (9)$$

In Equation 8, T = time in years, ρ_{b1} = initial bulk density after 1 year consolidation, and B = consolidation coefficient. Table 1 lists the values of ρ_{b1} and B as functions of reservoir operation.

It should be noted that the sediment motion is statistical in nature due to the fluctuating character of the acting forces.

Soil erosion

Soil erosion starts with the detachment of soil particles by the kinetic energy and momentum of rainfall. The main variables at this stage are rainfall intensity and duration, drop size, and impact velocity. The detached soil particles are subsequently transported downslope by surface runoff (for a summary see Shen, 1971). Surface runoff causes

sheet erosion at its initial stage when the flow velocities are low. Here the main feature is the uniform removal of soil without the development of visible water channels. Rill- and gully-type erosions develop successively as the surface runoff flow increases. Rill erosion is the soil removal from the topsoil layer through many small channels. Rill erosion is hardly visible. Gully erosion is the severe stage where deep channels resembling large ditches are cut through the soil. Substantial amounts of soil are transported by gully erosion. Surface erosion normally occurs when the land slope is at least 2%.

The fundamental causes of both erosion types are the absence of vegetation and unsuccessful soil conservation policies by the agriculture industry. The sediment transport mechanism in both cases is similar to that found in narrow rivers with high slopes. However, the estimation of soil erosion rates requires the application of other methods. The worldwide total sediment yield in the different river basins shows a significant variation from 0.01 t/km² year to several thousand tons. Lahlou (1996) gives illustrative statistics for 73 dam sites in North Africa (Morocco, Algeria, Tunisia). Table 2 summarizes some of the statistics. The sediment yields are very high in comparison with the large rivers in the world (Table 3). The high values are correlated with the extensive reservoir sedimentation problems in these countries.

River processes

In their natural environment, all rivers display a number of classical features, among which are a meandering of the river channel and the formation of different types of river beds (i.e., ripples, dunes, and anti-dunes) and the formation of various types of sand banks and bars. The river channel sediment transport capacity is controlled by the hydraulics of the flow (applied shear stresses), the sediment properties, and the hydrological variables. The available and supplied sediment to the river undergoes different modes of transport during its path along the river. There are two major transport modes: bed load transport and suspended load transport. Bed load transport is the movement of sediment particles in contact with the bed by rolling, sliding, and jumping. Suspended load is transported by the diffusion action of turbulence. The origin of the transported materials is important. The transport that has its origin in a river bed is known as

Reservoir Sedimentation, Table 1 Initial bulk density (kg/m³) and coefficient B for consolidation conditions

Reservoir operation	Sand		Silt		Clay	
	ρ_{b1}	B	ρ_{b1}	B	ρ_{b1}	B
Sediment always submerged or nearly submerged	1,500	0	1,050	90	500	250
Normal to moderate reservoir drawdown	1,500	0	1,185	45	750	170
Normal reservoir drawdown	1,500	0	1,275	15	950	100
Reservoir normally empty	1,500	0	1,320	0	1,250	0

Reservoir Sedimentation, Table 2 Sediment yields and reservoir sedimentation rates in North African countries (Lahlou, 1996)

Country	Number of dams	Annual sediment yield (t/km ² year)	Rate of reservoir sedimentation (10 ⁶ m ³ /year)
Algeria	39	85–2,500	0.04–1.86
Morocco	16	260–5,900	0.23–11.17
Tunisia	18	160–5,070	0.204–5.5

Reservoir Sedimentation, Table 3 Annual sediment yield and suspended sediment for 11 major rivers (Allen, 1997)

River	Drainage area (km ²)	Mean flow discharge (m ³ /s)	Annual sediment yield (t/km ² year)	Annual suspended load (Mt/year)
Amazon	6,150,000	200,000	187	1,150
Colorado (CA)	640,000	32	234	150
Mississippi	334,400	18,400	120	125
St. Lawrence	1,185,000	14,300	4	3
Rhine	225,000	2,243	0.72	17
Volga	1,350,000	8,400	26	19
Niger	1,112,700	6,020	32	29
Nile	2,715,000	317	46	125
Ganges	980,000	11,600	535	524
Yellow	98,000	2,858	120	122

bed-material transport. Here, the transport mode (either bed load or suspended load) is determined by the bed sediment composition and flow conditions. The external supply of materials (surface erosion) is known as wash load and is not directly related with the river channel flow. Wash loads are normally composed of very fine to coarse silt (4–60 μm) that is transported in suspension. To distinguish between the two material origins is of importance for reservoir sedimentation. Wash load is the main contributor from the river to the reservoir sedimentation. Surface erosion models are needed to estimate the wash load. The annual suspended sediment yield of the major rivers in the world is reported to be 20×10^9 t (Holeman, 1968). Table 3 gives a summary of the annual sediment loads and the sediment yields for ten major rivers in the world (Allen, 1997). It is interesting to note that the sediment yield from the Amazon River basin is relatively low compared to its drainage area and to other major rivers such as the Colorado River and the Ganges River. A major part of the Amazon Basin is covered with dense tropical forest that limits the sediment yield from the basin.

The three other important sources of sediment are riverbank erosion, landslides, and reservoir shoreline erosion. In many cases, riverbank erosion is a natural process that is partly related to the meandering of the river. Figure 2 shows an example of riverbank erosion in the upper river reach of Klarälven, which enters Sweden in the north of the county of Värmland. Riverbank erosion can in some cases be the major contributor to the total sediment load in a river. The U.S. Soil Conservation Service (Serr, 1971) found that the principal sediment sources in the Eel River basin were riverbank erosion (64%), landslides (26%), and sheet and gully erosion (10%). Significant amounts of sediment can enter the river or reservoir by landslide on the valley walls of rivers. The landslide can also act as a natural dam if the eroded material is sufficient to fill the waterway. In such cases upstream flooding can occur. Landslides are related to the topography, geology, and drainage, and flood periods are particularly dangerous in both cases. The landslide handbook (Highland and Bobrowsky, 2008) given by a U.S. Geological Survey is a valuable source of information on the various aspects of landslide and its mitigation.

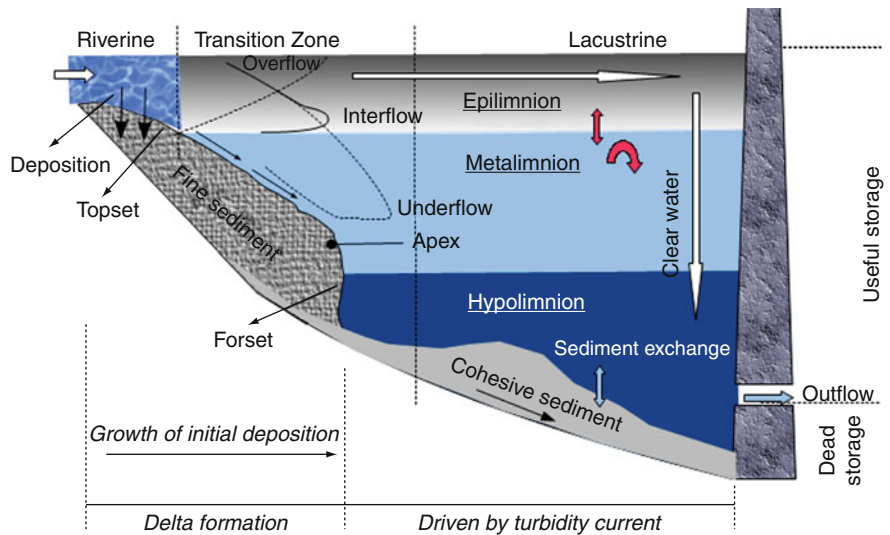
Reservoir sedimentation processes

The flow in a reservoir is driven by many meteorological parameters such as wind speed and its direction, and the various parameters that are related to the heat energy balance (e.g., temperature, dew point, radiation, and cloud cover). The complex three-dimensional nature of the reservoir flow structure is evident in terms of its thermal stratification, hydrodynamic instabilities, and large numbers of recirculation flow regions with varying size and strengths. There is ample scientific evidence on the influence of the reservoir flow on the characteristics of sediment transport and thus sedimentation in the reservoir (Xing et al., 2002; Scully and Friedrichs, 2003). To understand the reservoir sedimentation, some general reference to flow structure within the reservoir is needed. Figure 3 shows a simplified general view of the ongoing processes in a reservoir along a longitudinal section. The various flow and sediment transport regions are marked at an intermediate sedimentation stage.

A complex mixing process prevails within the reservoir and affects the sediment transport characteristics in the reservoir. Most reservoirs are temperature stratified along the flow depth, having three classical layers of epilimnion, metalimnion, and hypolimnion in the order of decreasing temperature with the flow depth (Martin and McCutcheon, 1999). The top epilimnion layer is warmer and normally well mixed. The stratification in freshwater reservoirs is driven mainly by solar energy, and to a lesser extent, by wind. The river entering the reservoir interacts with the low momentum reservoir in three distinct mixing regions, i.e., riverine, transition, and lacustrine. In the first region the advective forces dominate and keep the water column well mixed. The second region is an intermediate stage between riverine flow and lake flow in which the buoyancy forces (due to density difference) start to increase. In this region the buoyancy forces dominate over the advective forces. The river inflow gives rise to an overflow if its temperature is higher than the ambient temperature and to an underflow if its temperature is lower than the ambient temperature. The temperature differences between the river flow and the ambient reservoir water cause the formation of density currents. Density currents play a fundamental role in reservoir sedimentation. Here,



Reservoir Sedimentation, Figure 2 Riverbank erosion in the upper reach of the river Klaräven, Värmland, Sweden.



Reservoir Sedimentation, Figure 3 A schematic of sedimentation mechanism within a reservoir.

the key parameter is the Froude number based on the density difference:

$$Fr' = \frac{U_r}{\sqrt{g'h'}}, \quad g' = g \frac{\Delta\rho}{\rho} \quad (10)$$

in which U_r = relative velocity between the fluid layers, h' = thickness of density current layer, g = acceleration of gravity, ρ = density of the upper layer, and $\Delta\rho$ = density difference between upper and lower fluids. Another

important parameter for a flow with a density current is the Richardson number defined by

$$Ri = \frac{1}{Fr'^2} \quad (11)$$

The movement of a turbidity current depends on the entrainment of the ambient flow, which is related to the Richardson number by an entrainment coefficient, i.e., $E_u = f(Ri)$. For values of $Ri = 1$ or less, the entrainment is negligible.

The underlying mechanism for reservoir sedimentation is the formation of a special type of density current known as turbidity current. The turbidity current in turn is related to the rate of settling of sediment particles, sediment sorting, and the capacity of the reservoir flow to maintain sediment suspension. Sediment loads are discharged into the reservoir by the river in three parts: (1) bed load, (2) suspended load, and (3) wash load. The type and amount of the loads delivered to the reservoir are controlled by the hydraulics of the river, the geometry of the reservoir, and the section aspect ratio at the entrance to the reservoir (width to depth ratio). Generally, the coarser sediment (sand) does not reach the reservoir because of the aggradation effect of the dam that can travel several kilometers upstream of the entrance to the reservoir. The deposited material is primarily silt and clay. A typical distribution of the sediment types is given in Table 4, which shows the accumulation of sand (bed load) at the entrance of the reservoir. The mid region of the reservoir is dominated by silt, whereas in the outlet area, the clay and silt contents are almost equal. The table also confirms the process of sediment sorting as the deposition layer approaches the dam. The entrance deposition region is commonly known as delta formation. The content of sand can increase by erosion or landslide of the reservoir banks.

The sedimentation process in a reservoir is complex and makes generalization difficult. The details and the structure of deposition patterns are in many cases site dependent. However, the main aspects of the sedimentation process can be considered in three phases that correspond to different regions of the reservoir.

Phase one – This phase begins when the river enters the reservoir. At the entrance to the reservoir, the sediment transport capacity of the river is reduced considerably because of the loss of river flow momentum to the low-momentum reservoir water as well as the dissipation by the river bottom shear stresses. The sediment deposition starts first with larger sediment particles that are transported into the reservoir as bed load (delta formation). The finer sediment particles are suspended by the strong flow mixing in the riverine region. Here, an important issue is the mechanism of delta formation. To clarify this issue, a simplified three-dimensional flow simulation was done for the Ichari Reservoir in India. The longitudinal profile and the flow data were obtained from the Atkinson report (1996). The design storage capacity of the reservoir was 11.55 Mm³ with an annual inflow of 5,300 Mm³. Figure 4

shows the simulation result for a longitudinal cross section of the reservoir. The upper plot shows the path line for the entire reservoir. The lower plot is the enlarged flow paths and velocity vectors at the entrance to the reservoir. The figures clearly indicate a large recirculation flow region as the flow undergoes a three-dimensional boundary layer separation at the reservoir entrance. The reattachment point extends to a distance of about 20% of the total reservoir length. The large recirculation region acts as a sediment trap to cause deposition (delta formation). The formation of large delta regions in the early stages in the Ichari Reservoir in India gives some support to the analysis. The foregoing discussion illustrates the importance of the interaction of the river flow and the reservoir topography at the entrance. However, there might be other mechanisms for the formation of delta regions.

Phase two – In this phase, a part of the suspended sediment is transported to the transition zone at sufficiently high flow velocities. As the particles in the upper flow region start to settle, the sediment concentration begins to decrease from the water surface toward the reservoir bottom. The settling process is faster than a single particle due to the flocculation structure among the cohesive sediment particles. The settling velocity can be 1/100 or even as low as 1/1,000 of a single-particle fall velocity. The sediment concentration increases within the bottom sediment laden flow. A dense underflow layer forms due to the higher density of the mixed sediment. Equation 12 gives the increase in density for the mixed sediment flow:

$$\rho_m = \rho_0 + (\rho_s - \rho_0) C \quad (12)$$

in which ρ_0 = clear water density, ρ_s = sediment density, and C = sediment concentration.

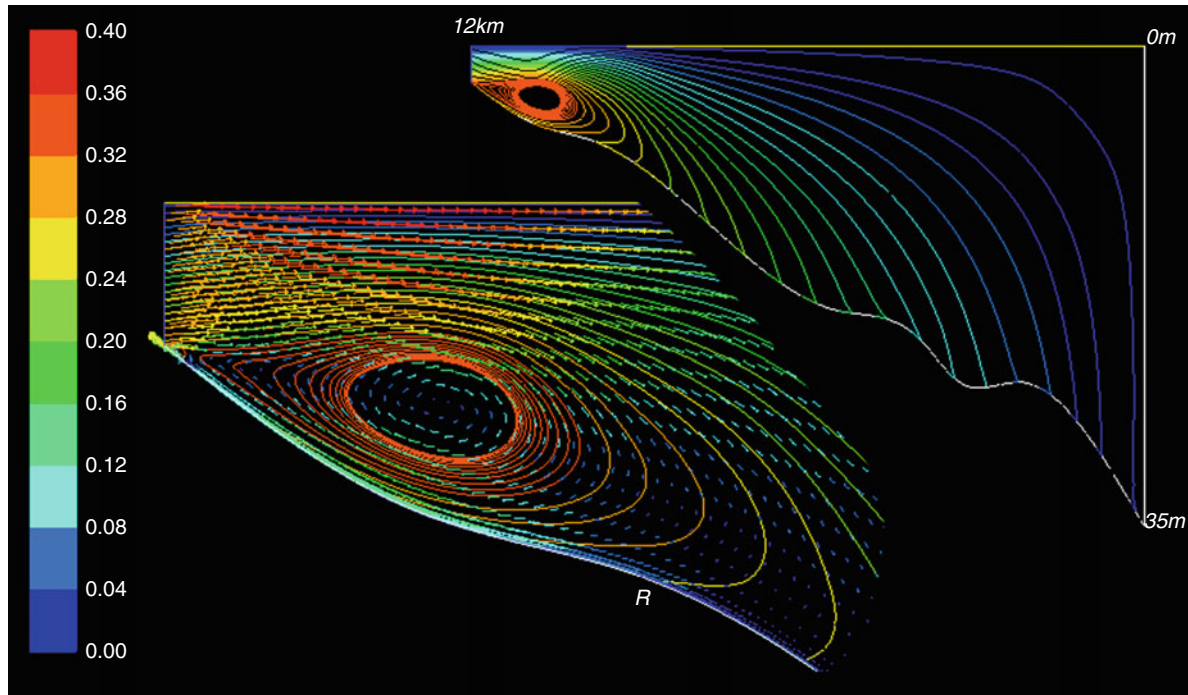
The underflow undergoes a transition from a sediment-laden flow to a turbidity current. During its movement toward the dam, the turbidity flow drags with it a part of the clear water above the interface. To maintain the flow continuity, the other part of the clear water in the upper region must flow backward. The reversal flow often brings any floating material to the surface. The presence of such material can confirm the formation of a turbidity current (Chien and Wan, 1999). Here, the condition for formation of the turbidity current is given by Equation 13, which is based on field and experimental data (Chien and Wan, 1999):

$$\frac{q^2}{\frac{(\rho_s - \rho_0)}{\rho'} g h_0^3} = 0.6 \quad (13)$$

in which h_0 = the water depth at the formation point of the turbidity current, q = flow discharge per unit width at h_0 , and ρ' = density of turbidity flow. From Equation 13, one may conclude that for a constant water level upstream of the dam, with increasing q the turbidity current will move toward dam and an increase in sediment concentration will push back the turbidity current. Thus, high sediment concentration in the riverine region will confine a turbidity

Reservoir Sedimentation, Table 4 A typical distribution of deposited sediment in a reservoir (USACE, 1987)

Particle size	Inlet (%)	Mid-reservoir (%)	Outlet (%)
Sand	5	<1	0
Silt	76	61	51
Clay	19	38	49



Reservoir Sedimentation, Figure 4 3-D flow simulations of the Ichari Reservoir, India, along a longitudinal cross section. Velocity and streamlines; *R* reattachment point of the separated boundary layer. The lower part is the magnified flow separation region. Fluent, RNG Transient Model, Dargahi (2010, not published).

current within a short distance from the reservoir entrance. The movement of the turbidity current toward the dam will continue as long as the longitudinal slope is sufficient to counteract the friction resistance. The propagation speed of the current can be estimated from Equation 14 if the layer thickness (h') is much smaller than the flow depth:

$$U_f' \approx 1.1 \sqrt{\frac{\Delta \rho}{\rho_0} g h'} \quad (14)$$

Equation 14 implies that the speed is independent of the bed slope. However, this is only valid for slopes below 4%. At higher slopes the coefficient 1.1 is a variable (Chien and Wan, 1999). Phase two is characterized by the formation of a fine sand to silt delta region and a mixture of silt and clay in the middle region. There are different possible scenarios on the temporal growth of the delta region. The region can emerge with the bottom layer disposition to form a more or less uniform layer throughout the reservoir. It can also continue to grow with a mechanism similar to the classical riverbed forms such as dunes and anti-dunes. Once an initial deposition forms, the temporal sediment accumulation continues (Figure 3, fine sediment). The deposition grows in size resembling a delta formation. It then propagates downstream as the sediments are removed from the top set and deposited on the forest (Figure 3). The growth and movement of the dune continues until a stage of dynamic equilibrium is

reached. One other scenario is the nonequilibrium stage caused by the transient flow and sediment load boundary conditions at the reservoir inlet.

The third sedimentation phase concerns the turbidity current entering the clear water lacustrine zone. Here, the thickness of the turbidity current increases further and a large clay deposition region forms behind the dam. A dynamic equilibrium stage can be reached if the turbidity layer slope decreases sufficiently to counteract the driving force of the turbidity current. However, to ensure such a condition, there must be an overall dynamic equilibrium prevailing in the river, implying that a natural armor layer (erosion protection) is developed along the riverbed, the river banks are stable, and the total sediment loads have decreased. The situation is rather unique and is more typical of mature rivers with limited surface soil erosion. An example is the reservoirs in Sweden that, even after 45 years, show little signs of any sedimentation of concern.

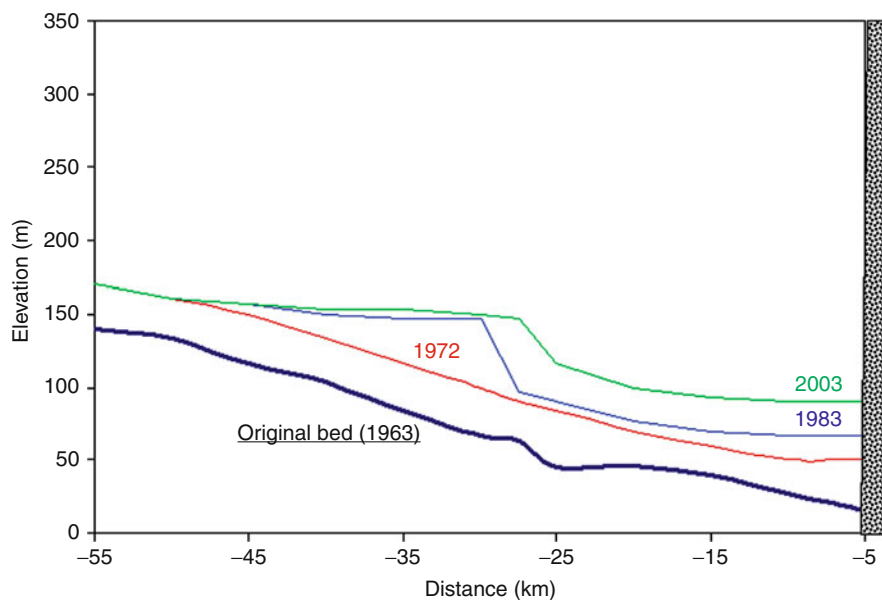
The foregoing sedimentation process is one possible scenario among many others. The main aspects are strong three-dimensional and transient characters of the process and the existence of different sedimentation patterns that normally appear along the lateral direction for the same reservoir. Three patterns of uniform, tapering, and wedge sedimentations are possible (Morris and Fan, 1997). The variations in the sedimentation patterns are partly caused by the dynamic boundary conditions. Another important

aspect is the sedimentation time scale. The sedimentation is a slow process in comparison with the flow time scale that can either halt after reaching some kind of dynamic equilibrium or may continue indefinitely until the entire reservoir is filled with sediment. The reported time spans are from 25 to 50 years.

Figure 5 shows an example of reservoir sedimentation in the Dez Reservoir. The dam was constructed in 1963 and is located in the Province of Khuzestan in southern Iran. It is a doubled-curvature concentric arch dam with a height of 203 m and a designed storage capacity of $3,315 \text{ Mm}^3$. The figure shows the various longitudinal sedimentation profiles for the period 1963–2003. The sedimentation rate was $20 \text{ Mm}^3/\text{year}$. The interesting feature is the formation of a uniform sedimentation layer in the initial 9-year period. The delta formation appears

from 1972 onward. The Dez Reservoir case clearly demonstrates the diversity and complexity of the sedimentation patterns in a reservoir. Furthermore, uniform deposits do not appear to be only a feature of narrow reservoir with small loads of fine sand as indicated by Morris and Fan (1997).

An example of extreme reservoir sedimentation is shown in Figure 6. It shows a photograph of the Gap weir, Werris Creek, NSW (Australia), on 13 June 1997 viewed from the left bank. The reservoir was fully silted in less than 25 years. Two examples of rapid sedimentation (12 years) are given by Atkinson (1996) for two reservoirs in India. The Welbedacht Reservoir in South Africa, completed in 1973 with a 152.2 million cubic meters storage capacity, lost most of its storage capacity (66%) within the first 13 years of its existence (Rooseboom, 1992).



Reservoir Sedimentation, Figure 5 The longitudinal sedimentation profile of the Dez Reservoir. (Data source Emamgholizadeh and Samadi, 2008.)



Reservoir Sedimentation, Figure 6 The Gap weir, Werris Creek, NSW (Australia), on June 1997 viewed from the left bank. (Courtesy of Professor Hurbert Chanson.)

Estimating sedimentation rate

The initial estimate of reservoir sedimentation rate can be obtained from a number of empirical design equations, and charts. Most of these equations are based on field data collected primarily in reservoirs in China and the USA. Their use in other cases requires some kind of calibration and validation. Two widely used methods are the Churchill method and Brune curve (see Morris and Fan, 1997). Churchill (1948) related the sediment release efficiency to the sedimentation index. The latter was defined as the ratio of the retention period to the mean flow velocity through the reservoir. The application of the method requires the storage volume, annual inflow, and reservoir length. A similar approach was suggested by Brune (1953) who related the capacity/inflow ratio (C/I) to the trap efficiency observed in reservoirs in the southeastern USA. Here, the trap efficiency (η) of a reservoir was defined as the ratio of storage capacity to the inflow. η is a function of age and shape of the reservoir, outlet type and its operation, and sediment characteristics. Various design curves were given to compute η as a function of C/I (Brune, 1953, Fig. 6).

Alternatively, the fraction of material deposited over the total settling basin length in percentage can be estimated from Equation 15 (Shen, 1971):

$$P = 1 - \frac{1}{e^{\frac{1.055l\omega_s}{Vd}}} \quad (15)$$

in which l = settling basin length in ft, ω_s = sediment fall velocity in ft/s, V = average flow velocity in ft/s, and d = water depth in ft. The equation yields the quantities of sediment deposited with given particle size. The total volume of sediment deposited in acre-feet is the sum of these quantities. The trap efficiency is calculated by dividing sediment inflow by the total sediment deposited.

The rate of loss of storage capacity (α in percent) for 25 reservoirs in China was found to be related to the annual rate of erosion (G), reservoir storage capacity (V), and drainage area (F), as estimated by Equation 16:

$$\alpha = 0.0002G^{0.95} \left(\frac{V}{F} \right)^{-0.8} \quad (16)$$

in which the units are G in t/km^2 , F in m^2 , and V in m^3 . Equation 16 applies to small and medium-size reservoirs (Xiaoqing, 2003). The same reference lists a set of empirical equations for estimating the depletion of the reservoir. Equation 17 gives the basic form:

$$V_t = V_0 \left(1 - \frac{W_s}{V_0} \right)^t \quad (17)$$

in which V_t = storage capacity at t years of reservoir operation, V_0 = initial storage, and W_s = annual sediment load (m^3).

The next step is to compute the reservoir capacity. A common method is the average-end-area method (Shen,

1971), which is based on taking the average of several areas of successive horizontal planes and multiplying the result by the contour intervals. The total reservoir volume (capacity) is then calculated by application of Simpson's rule.

A practical model called HYDROMED was used to compute the risk or the probability of reservoir sedimentation referred as to probability of failure in semiarid Mediterranean catchments (Ragab et al., 2001). The probability of failure was found to be low for the El-Gouazine catchment in Tunisia.

In recent years, a number of new methods have been used to compute the reservoir capacity and the sedimentation rate such as Cs-137 and GIS. Walling and He (2002) found the Cs-137 method useful for validation of distributed soil erosion and sediment delivery models. Durbude and Purandara (2005) give a successful application of remote sensing and GIS techniques to the Langanamakki Reservoir in India. The application of the Cs-137 method to reservoir sedimentation is growing. The main principal is to use Cs-137 to calibrate and validate soil erosion and sediment load models. McIntyre (1993) determined reservoir sedimentation from sediment cores with Cs-137 dating techniques. The dating techniques were correlated with reservoir sedimentation by relating sediment deposition to potential sediment production. The latter was determined by the Universal Soil Loss Equation (USLE).

Modeling of sedimentation

A two-step approach must be used to model the reservoir sedimentation successfully. The approach involves modeling the rate of sediment transport both at a larger river basin scale, and at the river channel scale. The basin model yields the sediment load or the erosion rate initiated by surface runoff and the kinetic energy of raindrops (precipitation). The river model quantifies the morphological characteristics of the river subject to sediment yield entering from the river basin. Presently, there are many different types of numerical models in both categories of basin and river modeling. However, there is an important fundamental difference between these categories. River basin models have a pronounced semiempirical nature that is mainly based on the concept of the Universal Soil Loss Equation. Expressed differently, the actual erosion processes are not modeled, whereas the river channel models are mainly theoretically based in their use of the fundamental equations of motion and mass conservation. The general features of each modeling approach are given. There are a large number of noncommercial and commercial models available. Here, the models were selected based on their extent of application, physical principals, and the ease and availability to the user. Commercial or license-based models are excluded from this discussion.

River basin erosion models

In their simplest form, these models relate the rate of soil erosion to rainfall characteristics. The rates of erosion

are separated into rainfall and runoff-induced (Shen, 1971). The transport by rainfall and surface runoff are given by Equations 18 and 19, respectively.

$$T_R = S_{TR}SI \quad (18)$$

$$T_F = S_{TF}q^{5/3}S^{2/3} \quad (19)$$

in which S_{TR} = soil transport coefficient, S = slope steepness, I = rainfall intensity, S_{TF} = soil transport coefficient by runoff, and q = runoff flow rate. The numerical values for the coefficients were given for soils found in the USA (Shen, 1971). The application of equations is straightforward; however, the site-specific coefficients must be estimated correctly.

A more general method is to use the USLE that incorporates many variables. The erosion yield from a river basin depends on a large number of variables, among which are the mechanical and dynamic properties of the soil; the type, size, and slope of the basin; and hydrological and metrological factors. These models have a general universal form given by Equation 20 for determining the mean annual soil loss A (t/ha/m-t):

$$A = RK (LS) CP \quad (20)$$

in which the soil erodibility is expressed by K (t/ha/m-t), R (t/ha/m-t) is related to rainfall force, LS is the hill length-slope factor (i.e., gravity force), and C and P are soil cover factors.

A general feature of USLE based models is their ability for long-term predictions of soil erosion. Jebari and Olsson (2009) give an example of the application of the USLE model in predicting soil erosion in semiarid regions of Tunisia. The two most commonly used models are Soil Water Assessment Tool (SWAT) and the Water Erosion Prediction Project (WEPP) model. The two models are process-based, distributed parameter, continuous simulation, and erosion prediction models. The sediment yield (Q_s metric tons) in SWAT is computed from Equation 2:

$$Q_s = 11.8(Q_{\text{surf}} q_{\text{peak}} A_{\text{hru}})^{0.56} K LS CP C_{\text{frg}} \quad (21)$$

in which Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is the peak runoff (m^3/s), A_{hru} is the area of HRU (ha), and C_{frg} is the coarse fragment factor. The SWAT model is widely applied to different regions of the world. An example is the application of the model to the Lake Tana Basin, Ethiopia (see Setegn et al., 2009). It should be noted that the models only account for long-term rill erosion and deposition processes; gully erosion is not included. Empirical equations are available for estimating the rate of gully and cave erosion (e.g., Xiaoqing, 2003). The WEPP model simulates three main physical processes of detachment, transport, and deposition. Surface erosion (inter-rill and rill) and channel erosion are summated as a function of shear stresses induced by flow. In an analogy with SWAT, WEPP does not model gully erosion. An interesting application of the WEPP model for slope analysis is given by Acharya and Cochrane (2009).

Another useful model is the WaTEM/SEDEM model that has its focus on the spatial variation of the related variables. WaTEM/SEDEM focuses on the prediction of water erosion and sediment delivery to rivers. The water erosion component is based on the Revised Universal Soil loss equation (RUSLE) for calculating mean annual soil loss values. The model can also simulate the impact of various scenarios of an integrated catchment management that includes soil conservation methods.

It should be noted that the applications of each of these models need extensive calibration and validation. The research results indicate that Cs-137 measurements can provide a good base for validation of the distributed soil erosion models such as WEPP (Walling and He, 2002).

The interested reader is referred to Bathurst (2002), where one finds some additional models and a comparison table. A complete list of various soil erosion models and download links are available at: http://soilerosion.net/doc/models_menu.html.

River channel transport models

General aspects

River channel models use different numerical methods to solve the conservation equations of mass and momentum. They range from simple, one-dimensional to complex, three-dimensional models. The basic one-dimensional equations for a river reach with area A , and an averaged velocity v read:

$$\frac{\partial(Av)}{\partial t} = -v \frac{\partial A}{\partial x} - A \frac{\partial v}{\partial x} \quad (22)$$

$$\frac{\partial(Av)}{\partial t} + \frac{\partial(Av^2)}{\partial x} = -Ag \frac{\partial h}{\partial x} + gA(S_0 - S_f) \quad (23)$$

in which h is the mean flow depth, S_0 is the channel bed slope, S_f is the friction slope which for a uniform flow could be obtained from the Darcy–Weisbach equation (f = friction parameter, g = acceleration of gravity, and R = hydraulic radius). The friction parameter is:

$$S_f = \frac{v^2 f}{8gR} \quad (24)$$

The sediment continuity equation is then used to compute the rate of change of the river bed:

$$\frac{\partial z}{\partial t} + \frac{1}{1 - \lambda} \frac{\partial q_s}{\partial x} = 0 \quad (25)$$

in which q_s = the total sediment discharge and λ = porosity. Modeling the sediment discharge is the underlying difficulty in applying Equation 25. Presently, there are no theoretical equations available for estimating the sediment load. The sediment discharge (bed or suspended loads) is estimated using semiempirical equations that are based on experimental data obtained from flume studies. There are a large number of equations available that have been applied with varying degrees of success (see Graf, 1971;

Chien and Wan, 1999; van Rijn, 1990). The latter is a comprehensive reversion of principals of sediment transport in rivers, estuaries, and coastal regions. Some popular equations with extensive applications are Engelund-Hansen (1967), Meyer-Peter and Muller (1948), Ackers and While (1973), and Van Rijn (1987). The bed load equations are normally based on the critical shear stress concept. They assume a general form given by Equation 26:

$$q_{s,b} = m(\tau - \tau_c)^n \quad (26)$$

in which m and n depend on the sediment properties and τ is the shear stress. Among available equations, the Van Rijn (1984) equation has shown promising results. It reads:

$$q_{s,b} = 0.053 \frac{T^{2.1}}{D_*^{0.3}} D \left(gD \left(\frac{\rho_s}{\rho} \right) - 1 \right)^{0.5}, \quad (27)$$

$$T = \frac{u_*^2 - u_{*c}^2}{u_{*c}^2}, \quad D_* = D_{50} \left(\frac{\rho_s - \rho}{\rho} \frac{g}{v^2} \right)^{1/3}$$

in which T = transport parameter, D_* = particle parameter, u_* = shear velocity obtained from the velocity profile or the water surface slope, D_{50} = particle diameter not exceeding by 50%, D is usually taken as D_{50} , and v = kinematics viscosity. Numerical methods are needed to solve Equations 22–25. The most common approach is based on a control-volume concept using a finite difference scheme. The domain is divided into a number of rectangular or curvilinear cells. The control volume method is then applied to each cell to ensure the conservation of mass and momentum within each cell (see Patankar, 1980). Some sediment models also account for sediment gradation and sorting as well as armor effects.

Modeling erosion in cohesive soils

The treatment of soil erosion in cohesive soils requires a different approach from that used for equations similar to Equation 27. It has been shown that for the range of bulk properties (ρ_b), the rate of erosion (E) in cohesive soils is well approximated with Equation 28 (Lick, 2009):

$$E = A \tau^m \rho_b^n \quad (28)$$

in which A , m , and n are constants. This equation is similar to Equation 26 that relates the rate of erosion to the excess shear stress. Good approximations for the coefficients are $n = 2.23$, $m = -5.6$, and A is assumed to have a value in the range $2 \times 10^6 - 4 \times 10^5$. The bulk density can be computed from Equation 9 in the case of reservoirs. Equation 28 can be rewritten as Equation 29 by defining the critical shear stress as the shear stress at which erosion rate is 10^{-4} cm/s:

$$E = 10^{-4} \left(\frac{\tau}{\tau_{co}} \right)^n \quad (29)$$

Equation 6 can be used to estimate the value of critical shear stress. In most numerical models that account for

cohesive sediment, Equations 28 and 29 are implemented. However, the use of these equations needs verification of the coefficients. Normally, the rate of erosion is determined in special types of hydraulic flumes such as SEDFLUME or rotating cylinder apparatus.

The application of sediment discharge equations requires the values of many hydraulic and sediment parameters. These equations have a limited scope and applicability to field situations due to their experimental character. To obtain a first estimate of the suspended load, regime-type equations can also be used. These equations have been widely used for many rivers in India and Pakistan in the design of stable channels. They relate the suspended sediment discharge (Q_s) to flow discharge (Q) by a power type equation, i.e., $Q_s = AQ^B$. The value of the exponent B is roughly 2 for a number of major rivers in Japan, Pakistan, Romania, and the USA (see Dargahi, 1985). For the Swedish rivers, the coefficients are $A = 2.4$ and $B = 1.6$. The regime equation gives only an estimate of the suspended load, which is still useful considering the fact that the suspended load is often a major portion of the total load in many rivers that enter a reservoir. The examination of the field data and experimental data shows that the bed load transport is on average about 20% of the total load. However, the ratio can show a great variation among different rivers. For example, Petkovic et al. (1999) indicated that total annual bed load transport in Serbia is about 10% of the suspended load. Emmett and Thomas (1978) give interesting field data on both bed and suspended loads in the Snake River near Lewiston, Idaho.

Available models

The available models can be classified into three groups: 1-D (including kinematic wave models), 2-D, and 3-D models. Table 5 gives a summary of the most common models.

The models in Table 5 are easily downloadable. Otherwise, the actual number of models exceeds the list (see Przedwojski et al., 1995). One-dimensional models give reasonable predictions of the morphological changes. They are relatively easy to use and the data requirements are not as extensive as for 2-D or 3-D models. The simplest form of 1-D models are kinematic wave models that are based on simplifications of Equations 22–25. They are especially suitable for studying the long-term response of a river to changes in the sediment load. They are also effective tools for initial investigation of the long-term sedimentation trends in reservoirs. In the previous section, the bases of the models, application areas, and the analytical solutions were presented (Equations 3 and 4). In contrast to the kinematic models, fully 1-D models offer a greater flexibility as the basic equations are fully model-solved for both steady and unsteady flow conditions. The other advantage is the possibility of modeling river networks. However, numerical methods must be used to solve the flow and sediment transport equations. Two popular models are HEC-RAS (HEC-6)

Reservoir Sedimentation, Table 5 Summary of downloadable flow and sediment transport models

Model name	Dimension	Application
DELTA	1-D simplified	Flow and sediment transport. Applicable to reservoir sedimentation. Valid for Froude numbers <0.6. The Fortran source code available (Graf, 1998)
HEC-RAS	1-D	Flow in river network flow, sediment transport, and water quality. Applicable to reservoir sedimentation. Hydraulic sorting included. Long-term predictions possible. Cohesive soil erosion is not modeled
HEC-6	1-D	Sediment transport model to calculate water surfaces and sediment bed surface profiles
CCHE1D	1-D	GIS based river network model for flow and sediment transport. Applicable to reservoir sedimentation. Cohesive erosion is not modeled
CCHE2D	2-D-depth averaged	River flow and sediment transport for non-cohesive graded sediment. Cohesive erosion not modeled
ECOMSED	3-D	General hydrodynamic, sediment transport, and water quality models. Applicable to rivers and reservoirs. Surface erosion models are not included. A large number of applications are available. These models can be used for long-term predictions Cohesive erosion is modeled
EFDC	3-D	
GEMSS	3-D-GIS based	
FVCOM	3-D	

and CCHE1D that are well documented with many application areas. A successful application of HEC-RAS is given by Emmett and Thomas (1978). They applied HEC-6 to Lower Granite Reservoir at Lewiston, Idaho to compute the bed profiles. The model results were used to evaluate the dredging needs associated with Lower Granite Reservoir.

The 2-D models are mostly depth-averaged models that bring the physics closer to 3-D models. In depth-averaged models, the vertical acceleration is assumed to be constant. Among various models, CCHE2D is a good model with documented applications (e.g., Dargahi, 2008). The disadvantage of this model is its limitation to non-cohesive sediment.

The final group of models is that of 3-D models as listed in Table 5. These models are comprehensive hydrodynamic, sediment transport, and water quality models. The listed models share many common features. To get some insight into these models, an outline of GEMSS is

given. GEMSS (Generalized Environmental Modeling System for Surfacewaters) is a state-of-the-art, 3-D, time-dependent hydrodynamic, transport, and water quality model that is embedded in GIS. The hydrodynamic and transport relationships are developed from the horizontal momentum balance, continuity, constituent transport, and the equation of state. The model accounts for the atmospheric forcing conditions (cloud cover, humidity, pressure, radiation, rainfall, solar energy, and wind speed and direction). It is applicable to both non-cohesive and cohesive sediments.

The foregoing 3-D models are particularly valuable tools for studying the flow and sediment transport characteristics in reservoirs. Their usefulness lies with their ability to account for the atmospheric forcing conditions, which are of significant importance as the primary driving force in reservoirs and other large open water bodies. There is a gap in the present knowledge about interaction of the stratified reservoir flow with the sediment loads discharged into the reservoirs. By using these state-of-art models, the subject of the reservoir sedimentation can be advanced to new horizons. However, the undertaking of the task would require extensive data for the boundary conditions and the reservoir itself. The data are needed both for the model setup and for the calibration/validation process. The possibility of success is good, given the extensive literature and published field data on this topic.

Mitigation methods

The mitigation of the reservoir sedimentation requires a system approach that compromises the river basin, the river channel, and the reservoir. The lack of an integrated design is of one the main reasons for many cases of extensive reservoir sedimentations around the world. No isolated measure can serve as a sustainable method. The mitigation should also be viewed in a larger perspective by understanding the socioeconomic aspects. The topic is beyond the scope of the present writing, but its importance is nevertheless emphasized. Preserving precious topsoil from erosion is one of the greatest environmental challenges of the twenty-first century. This preservation should be an inseparable part of a sustainable mitigation plan. A good teaching example is the successful mitigation plan of Coon Creek Basin in Wisconsin (Trimble and Lund, 1982).

Mitigation methods concern both the sedimentation sources and the actual reservoir sedimentation. The methods are applicable both prior to the construction of a dam and during its design lifetime. The mitigation methods can be classified into two groups: one concerns the river basin and the other deals with the sedimentation problem in the reservoir. Expressed differently, there is a need to address feasibility of mitigation methods for controlling the source of sediment supply and its consequences for a reservoir. It should be emphasized that there are no universal methods or solutions. The choice, feasibility, and success of a method are always dictated by

the local conditions. However, the execution of the task can greatly benefit from the enormous available resources of field applications and scientific advancements (e.g., Bruk, 1985; Palmieri et al., 2003; Xiaoqing, 2003; DFID, 2004; Althaus and Cesare, 2006; Lee et al., 2009). A schematic of the main methods is in Figure 7.

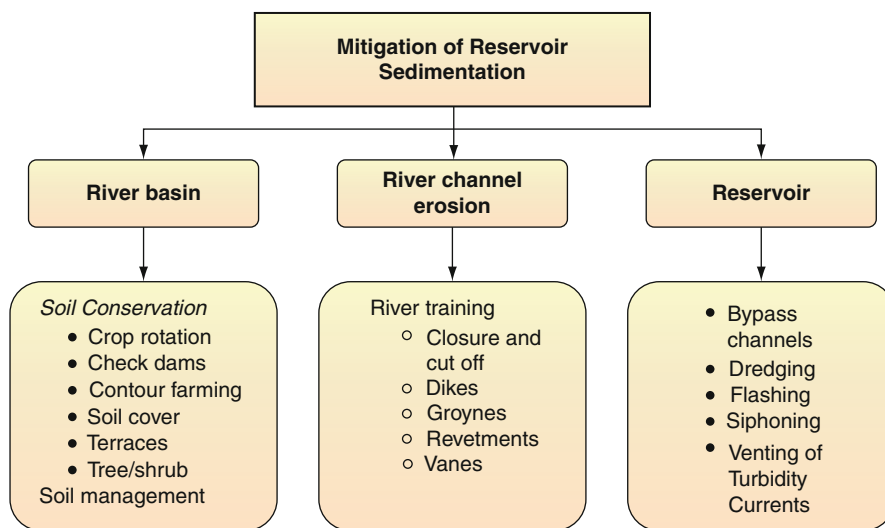
Soil conservation measures

The underlying concepts for the enforcement of various soil conservation measures include the reduction of the erosive power of the surface runoff flow and the maintenance of a good quality soil cover that enhances infiltration. These objectives could be achieved by changes in land management and/or the use of engineering structures. Sanders (2004) gives a comprehensive look into the various aspects of soil conservation. An indispensable source of information on soil conservation measures is the US National Conservation Practice Standards (2010) that is regularly published and updated by the Natural Resources Conservation Services (NRCS). It provides much valuable information on the use of a vast number of different conservation methods, among which are: terrace (NRCS, code 612), contour farming (NRCS, code 330), conservation cover (NRCS, code 327), conservation crop rotation (NRCS, code 328), and tree/shrub establishment (NRCS, code 612). Terracing the land is an effective method of reducing soil erosion and has been used around the world for centuries. An example of terracing is found in the famous Banaue rice terraces in the Philippines that are estimated to be 2,000 years old. There are many examples of successful implementation of terraces in China, Ethiopia, India, and Yemen. Rajan (1982) reports a significant reduction in the rate of sedimentation for Tungabhadra Reservoirs in India. A combined approach

of contour bunding, sediment trapping, and divergence of sediment laden flow was used. In a short 6-year period (1972–1978), the sedimentation rate was decreased from $96 \times 10^6 \text{ m}^3$ to $16 \times 10^6 \text{ m}^3$ per unit area. For the same period, the rate of reduction for Guanting Reservoir in China was 90% of the total amount of deposition (Bruk, 1985; Xiaoqing, 2003).

Flushing of the reservoir

Reservoir distillation by means of flushing is widely practiced in many parts of the world. The basic principal is to cause erosion in the deposited material by opening the bottom outlets of the dam. The effectiveness of the operation depends on many parameters, among which are the hydraulic conditions; the type, extent, and properties of the deposition; the reservoir water level; and the operation of the bottom outlets. Two types of flushing are possible: pressurized flushing and free-surface flushing (Morris and Fan, 1997). Pressurized flushing requires a moderate drawdown during which the pressurized hydraulic conditions prevail in the bottom outlets. In free-surface flushing, a free-surface flow condition is created in the bottom outlets when the water level reaches the level of the bottom outlets. The erosion characteristics are mainly localized for the pressurized case (e.g., Lai and Shen, 1996; Shen, 1999; Emamgholizadeh et al., 2005; Meshkati et al., 2009). The flow-induced shear stresses are only sufficient to cause a local flushing cone. The deeper the reservoir, the shorter the erosion distance upstream of the outlet. In reservoirs with low-level outlets for a flow discharge of 150 m/s, the erosion distance varies in the range 20–100 m, for reservoirs depths of 5 and 50 m, respectively (Atkinson, 1996). Figure 8 shows a photo of the pressurized flushing through the irrigation outlets at Dez dam. On June



Reservoir Sedimentation, Figure 7 A schematic of different reservoir sedimentation mitigation methods.



Reservoir Sedimentation, Figure 8 Pressurized flushing of the bottom outlets at the Dez Reservoir. (Courtesy of Dr. Emamgholizadeh.)

17, 2003, pressurized flushing was done that lasted for 4 h. The purpose was to remove the accumulated sediment ($D_{50} = 0.002$ mm) in the vicinity of the dam that was 30 m above the centerline of the irrigation outlets. A flushing cone with a diameter of about 400 m was created within a 100-m distance of the dam. The total volume of flushed sediment was 3 Mm^3 (Emamgholizadeh et al., 2005).

Free-surface flushing is recognized as an effective method in reducing reservoir sedimentation (e.g., Atkinson, 1996; Morris and Fan, 1997; White, 2000). It relies on the drawdown of the reservoir water level to the level of the bottom outlets and is more effective during flooding season. The sediment transport process is typically characterized by the rapid evolution of an erosion channel that extends upstream in the flood plain and deepens continuously. The process is commonly referred to as “retrogressive erosion.” Two main issues must be considered in using this method. One is its effectiveness and the other is the modeling of the flushing process in terms of the sediment load. The effectiveness of the free-surface flushing depends on the storage capacity and the shape of the reservoir. The method is effective in small reservoirs where the storage capacity is less than 30% of the mean annual flow and reservoirs in steep sided valleys (White and Bettess, 1984). Free-surface flushing is also restricted by the downstream impact of the enormous loads of flushed sediments. Atkinson (1996) lists six cases of successful reservoir flushing in India, Austria, China, Switzerland, and Venezuela. The recovery in storage capacity varied from 20% to nearly 100% of the original capacity. The flushing times varied from hours to 1.5 months. Cases of unsuccessful flushing concerned large reservoirs ($>14 \text{ M m}^3$) and errors in the design of

outlet structures. Two important criteria were developed by Atkinson (1996) for the feasibility assessment of flushing:

1. A sediment balance between the sediment mass flux and the sediment deposition during the flushing operation
2. A capacity criterion that assesses the long-term storage capacity

Numerical examples in using the two criteria were also provided.

Several methods are available for modeling the sediment transport characteristics during the flushing process. They range from empirical equations (Shen et al., 1993) to the application of 1-D morphological models (Lai and Shen, 1996) to more complex 2-D (Shen, 1999) and 3-D models (e.g., Khosronejad et al., 2008). However, the application of the latter models is limited. There are two major limitations to the application of these models, one is the proposed equations and models are often based on small-scale physical model studies and need many parameters that are site specific, and the second important restriction is the use of non-cohesive soil properties, which can be a serious concern. Cohesive soils are more erosion resistant than non-cohesive soils. The critical shear stress for the initiation of sediment motion can be 10 times higher than for non-cohesive sediment. The deposition can also have a consolidated character that further increases the resistance to erosion.

To estimate the sediment discharge for the free-surface case under uniform flow conditions, Equation 30 is proposed (Lai and Shen, 1996):

$$Q_{os} = E \frac{Q_o^{1.6} S^{1.2}}{B^{0.6}} \quad (30)$$

in which Q_o is the outlet discharge, m is the Manning coefficient, S = bed slope, B = flushing channel width, and E = coefficient of erodibility. The equation was partly based on field data collect in China. Values of 180, 200, and 650 were proposed for E . The lower the E value, the higher the erosion resistance. To determine the equilibrium channel width, Equation 31 is proposed:

$$B_e = 10.91 Q_d^{0.5} \quad (31)$$

in which Q_d = dominate discharge. The interesting feature of Equations 30 and 31 is their similarity to the regime (Lacey) equations for stable channel design. Regime equations were original developed by Lane for a river in India. The modified equation by Blench for the channel width is

$$B = k Q^{0.5} \quad (32)$$

$$K = \left(\frac{F_b}{F_s} \right)^{0.5}, \quad F_b = 1.9 d^{0.5} \quad (33)$$

in which d = sediment size in mm and F_s depends on cohesion properties of the sediment. F_s has assumed values of 0.1, 0.2, and 0.3 for slightly, medium, and highly cohesive sediments, respectively. The comparison of Equations 31 and Equation 32 shows the regime characteristics of Equation 31. It also suggests the importance of including the cohesion effect for estimating the equilibrium width of the flushed channel.

River bypass measures

An effective method to reduce the sediment inflow to the reservoir is the construction of bypass channels. The basic principal is to divert the sediment-laden flow through a channel or a tunnel. The method is especially effective during flood periods that carry high sediment concentrations. Compared to flushing, the method is more sustainable, but it requires large volumes of water during diversion. Bypass channels have been applied to many reservoirs in the world (Batuca and Jordaan, 2000). They are more effective in combination with low dams. An example is the Hushan Reservoir built in north China in 1969. By 1976, 54% of the reservoir capacity was lost due to sedimentation. The sedimentation rate decreased to 1/13 of the annual average following the construction of a small dam for flood detention at the entrance of the reservoir and a diversion channel. The channel diverted the sediment downstream of the dam (Bruk, 1985). Two other interesting successful cases are two small reservoirs in Switzerland. A 305-m-long diversion gallery was built at the small reservoir called Amsteg Reservoir. No sediment deposition was measured after 3 years of operation (Reed, 1931). The small Palagnedra Reservoir in the southern part of the country was subject to extreme sedimentation problems after its completion in 1953. No significant sedimentation was recorded following the construction of a diversion channel. Further successful applications are listed by Batuca and Jordaan (2000).

Mechanical removal

Dredging is a common method used to remove deposited sediments in small to medium-size reservoirs. The handbook on dredging gives a comprehensive review of the subject (Herbich, 1992). The method has many other application areas, among which are the maintenance of navigation channels, shoreline dredging, and creation of artificial islands. The type of the dredging equipment depends on the application area. Here, three main types of equipment could be used, i.e., dipper, bucket, and ladder. However, hydraulic dredging could be more advantageous as the unit is self-contained. It manages both the digging and the disposal of the material by either pumping or storing it in hoppers (Herbich, 1992). The method has two disadvantages. One is the high cost (about \$2–\$5/m³) and the other is the possible release of contaminated sediment. The dredging equipment creates a local flow field that is characterized by high levels of turbulence intensities and secondary

flow regions. Consequently, the contaminated sediment may cover the entire water column. In such cases, special equipment is needed (Herbich, 1992). RRESCON (Palmieri et al., 2003) gives a detailed analysis of both economical and technical aspects of sediment removal. The highest amount of sediment removed by dredging is reported as 11 million tons (same source). The amount might be the upper limit being manageable both economically and technically. Trucking is an alternative method that involves dry excavation and requires lowering the reservoir water level during dry seasons.

Siphon dredging

The method relies on using the hydraulic head available at dams as an energy source for dredging. Reh binder (1994) investigated the physics of the siphon dredging. The submersion depth appears to be the most important parameter. The theory indicates that right below the mouthpiece of the siphon, the sediment will be subject to compression and not to any lift. The method has been applied to small reservoirs around the world. In China, siphon dredging has been used for small reservoirs in semiarid regions. In these cases, the discharge range was 0.2–1.2 m³/s using pipes in the range 0.3 m–0.6 m. The maximum removed sediment concentrations were in the range 500–1,200 kg/m³ (Xiaoqing, 2003).

Sluicing of turbidity currents

Sluicing or venting of the turbidity currents through a low-level bottom outlet is a possible approach for reservoir distillation (Morris and Fan, 1997; Batuca and Jordaan, 2000). The success of the method depends on the proper location of the outlets and their operation. They should be synchronized with the turbidity currents and their discharge characteristics. The two foregoing issues limit the application of the method.

Normally, the method is most effective in narrow reservoirs. The release efficiency for a turbidity current is normally expressed as a function of reservoir length and the discharge ratio. The former is defined as the ratio of inflowing to outflowing turbidity current, and the latter is the ratio of flow rate of inflow to the turbidity release. The relationship between the two ratios was developed for Guanting Reservoirs and is given in a figure (Morris and Fan, 1997). The shorter the reservoir length, the higher the venting efficiency. Bruk (1985) gives many examples of turbidity currents and their venting in different reservoirs around the world. Sloff (1997) discusses the application of a two-layer computational model for computing the type of turbidity currents common in reservoirs. The model can be used to support the design and operation of the method. Two interesting cases are discussed by Muller and Cesare, 2009 for reservoirs Gigerwls and Mapragg in Switzerland. Large sediment loads were transported by turbidity currents into the Mapragg Reservoir during flood seasons. The opening of the bottom outlet caused the turbidity current to be

vented. The solid transport through the outlet was estimated as 6,000 t. It was also pointed out that if venting started at 2 g/L, the cost would equal to the cost of mechanical removal. The operation of the bottom outlet is automated to a threshold sediment concentration value. The outlet was closed when the sediment concentration fell below 2 L/g. The concept of automated operation is a good model for other reservoir sites where venting is an option. In recent years, the possibility of causing erosion in the fine bed sediment has been addressed in some research papers (e.g., Sequeiros et al., 2009). The basic idea is to erode the fine sediment by wall jets and the subsequent transport by a turbidity current. Experiments and a numerical model confirmed the applicability of the method; however, the results concerned only non-cohesive sediment.

Other measures

Riverbank and shoreline erosions could serve as significant sources of sediment to a reservoir. In those rivers that can maintain a natural dynamic balance state, riverbank erosion does not pose a serious threat, as the additional sediment load is often distributed within the river system. In other cases where anthropogenic activities dominate the riverbank, erosion is accelerated (e.g., Figure 2). In the section "River processes," it was noted that 64% of the total sediment load in California's Eel River originated from bank erosion. The extent of the problem will significantly increase if riverbank erosion assumes the character of a landslide. Landslides are known to deliver excessively large quantities of sediment to rivers. Similar problems could be encountered when shoreline erosion in reservoirs is an ongoing process. In these cases, the wind and the water level variations are the main causes of erosion.

In summary, reservoir sedimentation rate can be decreased by mitigating riverbank erosion and shoreline problems. In recent years, significant progress has been made in river training techniques (Przedwojski et al., 1995; Biedenharn et al., 1997; Beck, 2006). The popular techniques are revetments and groynes (Figure 7). However, the application of vanes holds promising results. The main methods used for counteracting landslides are change of slope, drainage, counter weight filling, anchors/walls, and chemical methods. Good coverage of the topic is found in many articles and handbooks (Cruden and Varnes, 1996; Highland and Bobrowsky, 2008; Acharya and Cochrane, 2009).

Environmental consequences

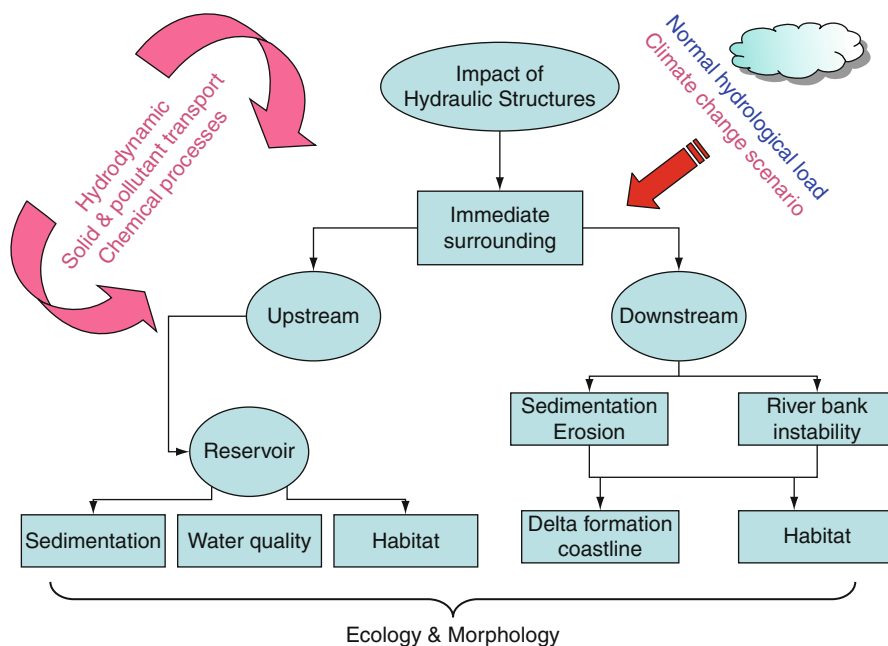
The future availability and development of sustainable and renewable energy sources hold the main key for the continuous progress and prosperity of human societies. Recent scientific developments confirm a trend of shifting from more fossil fuel-based energy sources to more environmentally acceptable sources such as wind energy and solar energy. Among the different sources of energy, traditional hydroelectric energy remains as an important

renewable source. The importance of hydropower lies in its potential for regulating and optimizing energy delivery as well as adaptation to the growing environmental demands. Despite all the benefits, the construction of a dam puts serious restraints on the environment. Here, only a general outline is given, as the details of the problem are beyond the scope of the present writing. The problems can be recognized in two different areas. One is the blockage effects on the intake structures as well as the risk for severe erosion of turbine components, including the blades. Sedimentation also results in a loss of revenues and availability of water for drinking and irrigation. The environmental problems occur both within and outside the reservoir. In the former case, the water quality may be affected due to nutrients and oxygen deficiency. A serious hazard will occur if the bottom sediment is contaminated with heavy metals and other harmful chemical substances. The oxygen deficiency is a consequence of chemical and bacterial reactions that consume oxygen. These in turn will threaten the fish habit. There is also a serious risk that the contaminated sediments could be released into the water body during reservoir flushing or similar operations. On a large scale, the imposed change on the river will adversely modify its morphological activities. Upstream of the dam, river bed aggradation increases flood risk and riverbank instability problems. The flood risk will increase significantly if the storage capacity of the reservoir is compromised. Downstream of the dam, serious morphological problems can occur such as extensive riverbed erosion, river bank failures, and modification of the delta regions and coastal lines. Some of these topics are adequately covered in many handbooks and articles (Shen, 1971; Bruk, 1985; Lahlou, 1996; Morris and Fan, 1998, and FISC, 2006). Figure 9 summarizes the foregoing facts.

Concluding remarks

Reservoir sedimentation is a process that involves the gradual accumulation of incoming sediment within a reservoir. The process is a result of a complex interaction between the various sediment transport processes that prevail in the river and the surface soil erosion within the basin as well as the hydrodynamics of the reservoir. The available field data suggest a worldwide loss in the storage capacity in the range of 0.5–1%.

There are several methods available to mitigate the sedimentation problem ranging from soil conservation measures to the mechanical removal of sediment. There is a need for a systematic approach that does not compromise the river basin, the river channel, or the reservoir. The lack of an integrated design is one of the main reasons for extensive reservoir sedimentations around the world. No isolated measure can serve as a sustainable method. In addition, mitigation should be viewed in a larger perspective by understanding the socioeconomic aspects. Soil conservation measures should be an inseparable part of a sustainable mitigation plan because they can help to



Reservoir Sedimentation, Figure 9 A schematic of possible impacts of hydraulic structures (dams), morphological and environmental aspects.

preserve the precious topsoil from erosion losses, which is of one the greatest environmental challenges of the twenty-first century.

To model reservoir sedimentation, both the rate of sediment transport at a larger river basin scale and at the river channel scale should be considered. The common approach for modeling soil erosion is to use models that are based on the Universal Soil Loss Equations (USLE). Modeling at river channel scale involves the use of numerical models based on the fundamental equations of motion and continuity. They range from simplified one-dimensional to three-dimensional models. The soil and river channel models yield the sediment load into the reservoir. The sedimentation process in the reservoir is normally estimated using semiempirically based design charts and equations.

The present extensive literature articles and case studies, as well as many useful handbooks, give a very good coverage on various aspects of reservoir sedimentation. However, there is a pressing need for further research. The need is in two areas: one is to gain a better insight into the interaction of the sediment inflow and the hydrodynamics of the reservoir and the second is the use of more-advanced models. Turbidity currents are recognized as a primary sedimentation mechanism. However, there is still a need for addressing the specific physical features of these currents within the reservoir. The latest improvements in numerical modeling make the application and development of advanced numerical models a feasible method for reservoir sedimentation. The availability of various large-scale hydrodynamic, sediment

transport, and water quality models can make the task possible. These models have two major advantages in comparison with those applied so far. The hydrodynamics of the reservoir are more accurately modeled by including the forcing atmospheric conditions. Second, the sediment transport models can account for both multilayer non-cohesive and cohesive sediments. Here, it should be noted that all models, irrespective of their nature and modeling dimension, must be carefully validated and verified. This aspect is especially important for soil erosion models.

Reservoir sedimentation can adversely affect the environment. These effects are apart from technical aspects, such as problems at intake structures and turbines. The possible environmental consequences are water quality problems within the reservoir, increased risk of flooding caused by river aggradation, negative impacts on wildlife, especially various fish species. There will be also a number of morphological and ecological consequences downstream of a dam. There is a pressing need to consider these issues in relation to the impact of possible climate change. In some regions of the world, it is foreseen that climate change may result in significant increase or decrease in surface runoff.

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Cross-references

[Nasser Lake Reservoir and Lake Trap Efficiency Reservoir Sedimentation Xiaolangdi Reservoir's Role in Water and Sediment Regulation](#)

RESERVOIR SEDIMENTATION IN AUSTRALIA UNDER EXTREME CONDITIONS

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Introduction

Since the early European settlements in Australia, the coastal and continental development of the country has been coupled with the availability of water supply. Today, the country's economy remains highly dependant upon its surface irrigation, and more than 85% of water diversions are for agricultural purposes (irrigation and stock watering only). Any reduction in water storage caused by reservoir siltation, and the associated loss of fertile soil, is a critical parameter with economical and political impacts. There has been, however, some conflicting information on whether reservoir siltation has been significant in Australia. Indeed, for many years, reservoir sedimentation has not been an issue: "the (sediment) yield [...] is relatively low compared to others in the world" (Outhet 1984, NSW Water Resources Commission); the classical text book *Open Channel Flow* by F. M. Henderson, University of Newcastle NSW, made no mention of reservoir siltation in Australia in the section "Sediment transport" (Henderson, 1966). The issue of reservoir siltation in

Australia was ignored and rejected until the late 1970s despite some implications in terms of dam safety (Chanson, 1998; Chanson and James, 1999).

Herein, a reanalysis of existing data and new information on extreme reservoir siltation in Australia is presented. It is shown that several extreme siltation events took place and affected predominantly small to medium size reservoirs. It is the purpose of the study to present new comparative data and to develop new compelling conclusions regarding reservoir sedimentation in Australia.

Hydrology of the Australian continent

Australia is a large continent ($7,690 \text{ E} + 3 \text{ km}^2$) of low relief (Figure 1). Its most prominent topographic feature is the Great Dividing Range, a chain of low mountains and tablelands extending over 2,500 km along the eastern and southeastern coastlines.

Although the average annual rainfall is about 420 mm, the spatial and temporal variability is high. The rainfall may vary from zero for several years during droughts to extreme hydrological events (e.g., 515 mm in 6 h at Dapto NSW, in 1984). The average runoff is only 13% of the rainfall, varying from 0 mm in most Western Australia to over 700 mm in some regions of Eastern Australia and Tasmania (Department of Natural Resources, 1976). Indeed, evaporation is high. Average annual standard pan evaporation exceeds 1,000 mm in nearly all parts of the continent, with extreme evaporation above 3,000 mm in Central Australia.

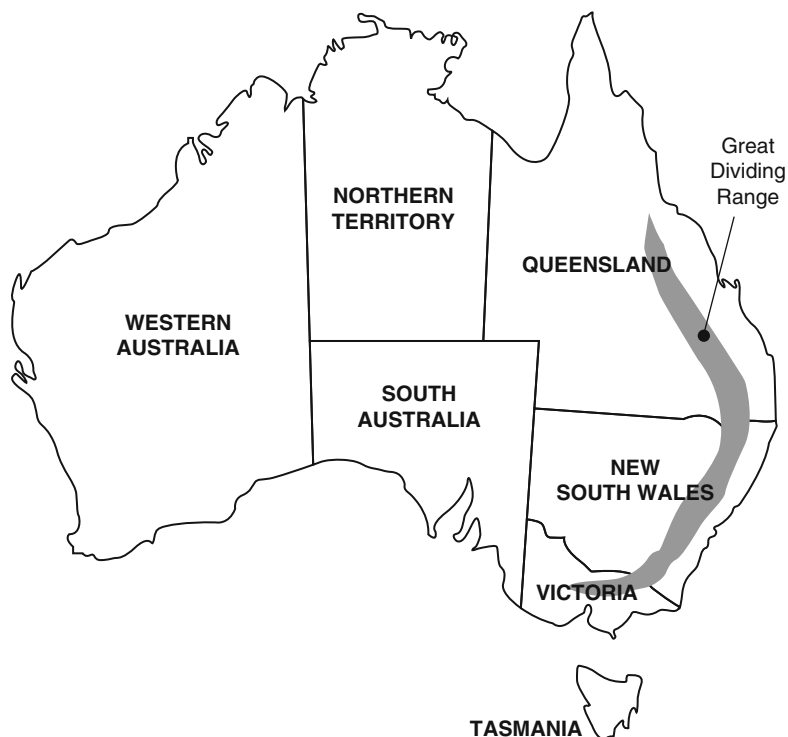
High evaporation coupled with the variability of surface runoff make conservation and development of surface water resources more expensive, less effective, and more political than in many countries.

Extreme reservoir siltation in Australia

Between 1890 and 1960, more than 20 reservoirs (excluding farm dams) became fully silted in Australia, most in New South Wales (Table 1). The writer investigated personally several reservoir siltation cases (Figures 2–5). Fully silted reservoirs included town water supply reservoirs (e.g., Moore Creek dam), railway dams (e.g., Gap weir), and mining reservoirs (The railway dams were built to supply water to the steam engines for the railway. Steam engines were in use in Australia up to the 1970s.).

Examples of reservoir siltation

Completed in 1888 (first dam) and around 1890 (second one), the Sheba dams were designed to supply water to the gold mines of the Mount Sheba Company, near Nundle NSW located next to the edge of the Great Dividing Range. The upper dam is an earth embankment (7.6 m high, 91 m long), and the reservoir area is 5 acres. The lower dam is also an earthfill structure (6.1 m high, 64 m long) with a 4-acre reservoir area. The dams are located at high altitude, nearly 1,100 m, on the western side of



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 1 Map of the Australian continent.

Reservoir Sedimentation in Australia under Extreme Conditions, Table 1 Major reservoir siltation in Australia

Reservoir (1)	Location (2)	Completion date (3)	End of use (4)	Purpose (5)
Sheba dams	Nundle, NSW	1888	– (*)	Mining (two dams)
Corona	Broken Hill, NSW	1890	1910 (*)	Irrigation
Laanecoorie	Maryborough, VIC	1891	Still in use	Irrigation
Stephens Creek	Broken Hill, NSW	1892	Still in use	Town water supply
Junction Reefs	Lyndhurst, NSW	1896	1930? (*)	Hydropower for mining activities
Moore Creek	Tamworth, NSW	1898	1924 (*)	Town water supply
Gap	Werris Creek, NSW	1902	1924 (*)	Railway supply
Pekina Creek	Orroroo, SA	1907	1984	Irrigation and town water supply
de Burgh dam	Barren Jack, NSW	1908	–	Railway and town water supply
Koorawatha	Cowra, NSW	1911	– (*)	Railway supply
Pykes Creek	Ballan, VIC	1911	Still in use	Irrigation and water supply
Pekina Creek	Orroroo, SA	1910	1930s (*)	Town water supply
Cunningham Creek	Harden, NSW	1912	1929 (*)	Railway supply
Illalong Creek	Binalong, NSW	1914	1985? (*)	Railway supply
Umberumberka	Broken Hill, NSW	1915	Still in use	Town water supply
Melton	Werribee, VIC	1916	Still in use	Irrigation
Korumbryn Creek	Murwillumbah, NSW	1918	1924? (*)	Town water supply
Borenore Creek	Orange, NSW	1928	Still in use	Railway supply and town water supply today
Quipolly	Werris Creek, NSW	1932	1955 (*)	Railway supply
Inverell	Inverell, NSW	1939	1982 (*)	Town water supply
Arrona Gorge dam	Leigh Creek Town, SA	1950	–	Mining and town water supply

Chanson (1998).

NSW New South Wales, QLD Queensland, SA South Australia, VIC Victoria, WA Western Australia

(*) reservoir fully silted today, (–) information not available.

the Great Dividing Range, and water was collected on both the western and eastern slopes of the Range. The dams are fully silted and used for trout fishing and as touristic attraction. There are some safety concerns because the spillways are inadequate.

Built around 1905–1907, commissioned in 1911, the Pekina Creek dam is an earthfill structure, 24 m high after the heightening in 1914. Located near Orroroo SA, it was designed to supply irrigation and town water. The original reservoir capacity was $1.54 \times 10^6 \text{ m}^3$ (after 1914 heightening), and the catchment area is 136 km^2 . More than 50% of the reservoir was silted in 1944, and the sediment volume accounted for 60% of the initial capacity in 1971. The reservoir was disused in 1964 (McQuade et al., 1981).

The Koorawatha dams, located near Koorawatha NSW, were a railway dams, designed to supply water to the steam engines for the nearby railway line, opened in November 1886 and closed in 1980. Two thin-arch concrete dams were built successively at the same site. The first dam was 5–7 m high, and it is located 5–10 m upstream of the present dam (Figure 2). The crest was still



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 2 Dry reservoir of Koorawatha weir, railway dam completed in 1911 – view from the right bank in December 1997.

visible during dry periods up to the 1930s although, today, it is underneath the dry reservoir bed. Completed in 1911 (or 1913?), the second Koorawatha dam is a concrete single-radius arch (9 m high, 0.92 m thick at crest, 40-m arch radius). The upstream wall is vertical, and the downstream face is battered. The weir was equipped with an outlet system and an overfall spillway (24 m long, 0.3 m high). The reservoir is fully silted today, occupied by sand and gravels, suggesting sedimentation by bed-load (Figure 2).

Completed in 1928, the Borenore Creek dam was built to supply water to the Orange-Broken Hill railway line. The dam is a concrete single-radius arch wall (17 m high, 123 m long at crest, 1.12-m crest thickness) (Figure 4). The catchment area is 22 km^2 , and the original storage capacity was $230,000 \text{ m}^3$. The dam was equipped with an outlet system and an overfall spillway. Interestingly, a new outlet (pipe inlet) was installed, later, about half-height of the dam, as a result of the reservoir siltation which amounted for $150,000 \text{ m}^3$ in 1981 (Figure 4). After being used by the NSW Railway Department, the dam has been used as the town water supply for Molong. The reservoir is used only as an emergency reserve today.

Completed in 1916, the Melton dam is an earth and rockfill embankment, and it was heightened in 1937 and 1967. The reservoir was built for irrigation purposes. The initial reservoir capacity of 21.0 Mm^3 was increased to 23.6 Mm^3 in 1937. The catchment area is $1,098 \text{ km}^2$. During the 1930s and 1940s, the reservoir suffered heavy siltation caused by cattle and sheep grazing, gold and coal mining, and rabbit colonies in the catchment. In 1941, when the reservoir was nearly empty, a heavy rainstorm filled the reservoir in 36 h and the spillway was heavily used. (The reservoir inflow was estimated at $1,444 \text{ m}^3/\text{s}$.) Massive siltation took place during the event, and a 2.6-m thick silt deposit was left on the spillway intake after the flood. In 1945, the reservoir capacity was reduced down to 19.1 Mm^3 . Erosion control works were carried out, including construction of check dams, furrowing works, and elimination of vermin. In 1968, the reservoir siltation amounted for 6.6 Mm^3 of sediments.

The old Quipolly dam or Quipolly dam No. 1 was completed in 1932 to supply town water for Werris Creek NSW, irrigation water and water for steam engines (Figure 5). The dam is a concrete single arch (19 m high, 184 m long crest), the catchment area is 70 km^2 , and the original storage capacity was $860,000 \text{ m}^3$. The reservoir suffered heavy sedimentation between 1941 and 1943 (Chanson and James, 1998). The reservoir was disused in 1955, and the reservoir is fully silted today. The reservoir acts now as a sediment trap for the new Quipolly dam (Quipolly dam No. 2) located downstream.

Comparison between Australian and overseas siltation rates

A comparative analysis of the siltation rates with overseas experience suggests that the reservoir sedimentation



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 3 Fully silted reservoir of Cunningham Creek railway dam (Harden NSW) completed in 1912 – view from the right bank in December 1997.



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 4 Borenore Creek dam completed in 1928 – view from the left bank in December 1997. Note the old scour outlet system and the new water intake at half-height of the dam wall.

rates in Australia were high (Table 2). Table 2 compares the most extreme (well-documented) siltation events in North Africa, North America, Asia, Europe, and Australia. These data are summarized in Figure 6,

showing extreme siltation rates as a function of the duration of the study.

Figure 6 suggests that highest (recorded) siltation rates are observed during short duration studies (1–10 years).



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 5 Fully silted reservoir of Old Quipolly dam (Werris Creek NSW) completed in 1932 – view from the right bank in June 1997.

There is, however, a lack of information on long-term siltation over 70 years. Note further that the data indicate the net sedimentation rate, after flushing. In several cases where flushing was used, the real sediment inflow rate was much larger.

Among the extreme events, the cases of the Shihmen reservoir, the El Ouldja dam, and the Sweetwater reservoir are peculiar. The Shihmen dam (Taiwan Republic of China) is a 133-m high dam built between 1958 and 1964. The maximum reservoir capacity was more than 60,000,000 m³, and the catchment area is 763 km². Although the dam was inaugurated in 1964, the reservoir began filling in May 1963. In September 1963, 20,000,000 m³ of silt accumulated during cyclonic floods (typhoon Gloria).

The El Ouldja dam was a debris dam built to protect the main Oued Djenden dam (Algeria). The siltation of the reservoir was studied in details between 1947 and 1950 (Duquenois, 1951). The results highlighted siltation by bed-load material with sizes ranging from 1 mm to over 0.5 m and heavily loaded turbidity currents of silt and clay (density between 1,100 and 1,300 kg/m³).

Built between 1888 and 1887, the Sweetwater dam was designed to supply irrigation and town water to the San Diego area (USA). The catchment area is 482 km², and the original reservoir capacity was 20 E + 6 m³. Heavy siltation took place during the January 1895 flood, and it was well documented (Schuyler, 1909).

In Australia, the sedimentation of Quipolly reservoir between 1941 and 1943 was an extraordinary event. Overall, most sedimentation problems in Australia were experienced with small to medium size reservoir (catchment area less than 100 km² typically). In contrast, large Australian reservoirs have not been sedimenting rapidly at the exception of Melton and Eildon reservoirs. Heavy siltation at Eildon was experienced in 1940 during torrential rainfalls, following bushfires which destroyed more than 50% of the forest in the catchment (Joseph, 1953).

Today, lower siltation rates are experienced in Australia, especially since the 1950s. It is believed that the reduction in sedimentation is related to the introduction of new farming techniques, new land conservations practices, and an awareness of soil erosion problems. The same trend is experienced in the New South Wales, Victoria, South Australia, and Queensland states (Figure 1).

Discussion: Climatic changes and flushing devices

Interestingly, the records suggest that the most extreme siltation periods in Australia took place during major floods following an El Niño event and long droughts. Such extreme siltation events were experienced at the Junction Reefs reservoir (1902 floods after the Great Drought of 1900–1902), the Moore Creek reservoir (flood of February 1908), the Gap weir (floods of 1919), the Melton reservoir (flood of 1941), and the Quipolly reservoir (floods of 1942–1943).

The drought periods in Australia may be extremely severe. The most severe drought occurred between 1895 and 1903, 1902 being the severest year. During this period, the sheep numbers declined by more than 50% and cattle by more than 40%. Recently, a decade of drought persisted between 1958 and 1968, and between 2000 and 2008.

The world community has focused its attention on the early detection of drought (*El Niño*) which is termed a “major catastrophe” in the television news. But the El Niño phenomenon, also called El Niño Southern Oscillation phenomenon (ENSO), takes place in average every 5–7 years. It is a *recurrent* climate pattern which is not properly managed by local, national, or international institutions. No contingency for long-term policy has been made.

Sediment flushing devices (or lack of)

Surprisingly, the Australian reservoirs have been inadequately equipped with flushing devices (Table 3). Most

Reservoir Sedimentation in Australia under Extreme Conditions, Table 2 Examples of extreme reservoir siltation rates in Australia and overseas

Reservoir (1)	Sedimentation rate (m ³ /km ² /year) (2)	Study period (3)	Catchment area (km ²) (4)	Annual rainfall (mm) (5)
<i>Asia</i>				
Wu-Sheh (Taiwan) (S)	10,838	1957–58	205	–
	9,959	1959–61	205	–
	7,274	1966–69	205	–
Shihmen (Taiwan) (S)	4,366	1958–64	763	> 2,000
Tsengwen (Taiwan) (S)	6,300	1973–83	460	3,000
Muchkundi (India)	1,165	1920–30?	67	–
<i>North Africa</i>				
El Ouldja (Algeria) (W)	7,960 (F)	1948–49	1.1	1,500
El Fodda (Algeria) (W)	5,625 (F)	1950–52	800	555
	3,060 (F)	1932–48	800	555
Hamiz (Algeria) (W)	1,300	1879–1951	139	–
El Gherza (Algeria)	615	1951–67	1,300	35
	577	1986–92	1,300	35
<i>North America</i>				
Sweetwater (USA)	10,599	1894–95	482	240
White Rock (USA)	570	1923–28	295	870
Zuni (USA) (*)	546	1906–27	1,290	250–400
Roosevelt (USA)	438	1906–25	14,900	–
<i>Europe</i>				
Saifnitz (Austria) (*)	6,820	1876	4	–
Monte Reale (Italy) (*)	1,927	1904–05	436	–
Wetzmann (Aust.) (*)	1,852	1883–84	324	–
Pont-du-Loup (France) (*)	1,818	1927–28	750	–
Pontebba (Austria)	1,556	1862–80	10	–
Lavagnina (Italy)	784	1884–1904	26	1,800
Roznov (Poland) (S)	398	1958–61	4,885	600
Cismon (Italy)	353	1909–19	496	1,500
Abbeystead (UK) (*)	308	1930–48	49	1,300–1,800
Porabka (Poland) (S)	288	1958–60	1,082	600
<i>Australia</i>				
Quipolly (*)	1,143	1941–43	70	686
Pykes Creek	465	1911–45	125	–
Umberumberka	407	1961–64	420	220
Corona (*)	400	1890–1910	15	–
Eildon	381	1939–40	3,885	–
Moore Creek (*)	174	1911–24	51	674
Pekina Creek (*)	174	1911–44	136	340–450
Korrumbyn Creek (*)	1,400 (?)	1918–24?	3	1,699

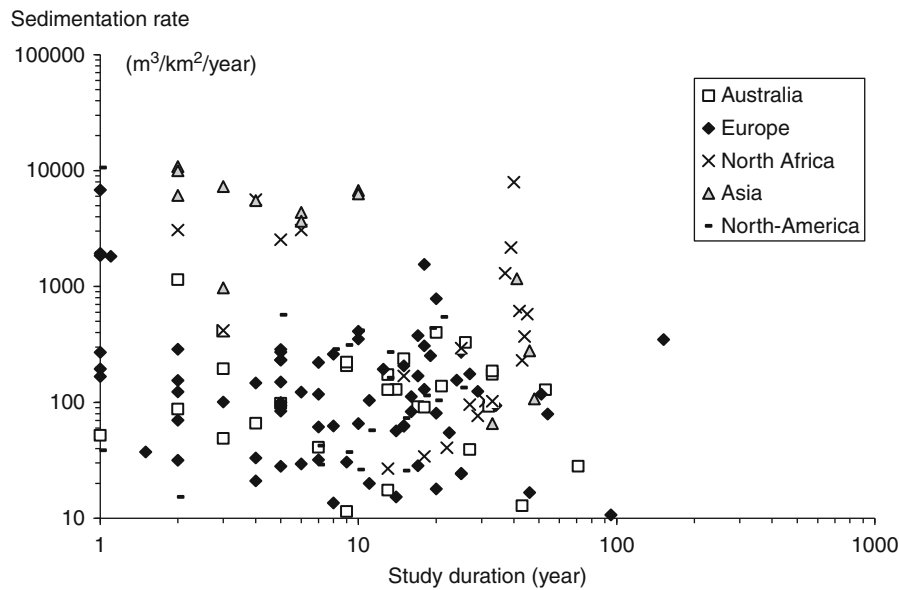
Chanson (1998), Chanson and James (1998), Chu (1991), Cyberski (1971), Lajczak (1994), Orth (1934), Rowan et al. (1995).

(S) Summer rainfall climate, (W) Winter rainfall climate, (F) Important flushing, (*) fully silted reservoir, (?) uncertain data, (–) Data not available.

Australian reservoirs were equipped with a single-scour outlet ($\varnothing = 0.3$ to 0.5 m), inadequate to desilt a reservoir. Only few dams were equipped with two or more flushing systems e.g., the Illalong Creek dam completed in 1914 and now fully silted.

In comparison, the Nabataeans, Romans, and Spaniards equipped their reservoirs with large sediment flushing system. (The Nabataeans were the habitants from an ancient kingdom to the East and Southeast of Palestine that

include the Neguev desert. The Nabataean kingdom lasted from around B.C. 312 to A.D. 106. The Nabataeans built a large number of soil and retention dams. Some are still in use today.) For example, the Roman engineers equipped the Monte Novo dam (A.D. 300, Portugal) with two outlets of 1.2 and 1.4 m² cross-sectional area each. Such an expertise in sediment flushing, gained over the past 22 centuries, was obviously unknown to, or forgotten by, the Australian engineers.



Reservoir Sedimentation in Australia under Extreme Conditions, Figure 6 Extreme siltation rates ($\text{m}^3/\text{km}^2/\text{year}$) as a function of study duration (year).

Reservoir Sedimentation in Australia under Extreme Conditions, Table 3 Scour outlet systems

Dam (1)	Year of compl. (2)	H (m) (3)	Catch. area (km^2) (4)	Reserv. capac. (m^3) (5)	Bottom outlets (6)	Outlet area (m^2) (7)
Nabatean dam Sabra valley dam, Jordan	BC 100	4.6	—	3,600	1 outlet	0.49
Roman dams						
Kasserine dam	BC 100	10	—	—	Vaulted outlet tunnel	4
Örükaya dam, Çorum, Turkey	AD 200	16	—	—	Vaulted bottom outlet	3
Çavdarhisar dam, Kütahya, Turkey	AD 200	7	—	—	Vaulted bottom outlet	11
Monte Novo, Evora, Portugal	AD 300	5.7	2.9	—	2 outlets (1.2 and 1.4 m^2)	2.6
Spanish dams						
Almansa dam, Spain	1384	15	—	2,800,000	2 water outlets + 1 scour outlet (1.95 m^2)	2.95
Alicante (Tibi) dam, Spain	1594	41	—	5,400,000	1 water outlet + 1 scour outlet (5 m^2)	6
Elche dam, Spain	1642–45	23.2	—	400,000	vertical outlet + scour gallery	—
Relleu dam, Spain	1650–1776?	28	—	600,000	large scour gallery	—
Puentes dam, Spain	1791	50	—	52,000,000	2 water outlets + scour gallery (51.1 m^2)	>52
Australian dams						
Moore Creek dam, Australia	1898	18.6	51	220,000	1 pipe outlet + 1 scour valve	~0.1
Gap weir, Australia	1902	6–10	160	—	No outlet	0
Korrumbyn Creek dam, Australia	1919	14.1	3	27,300	1 pipe outlet + 1 scour valve	0.04
Old Quipolly dam, Australia	1932	19	70	860,000	1 pipe outlet + 1 scour valve	~0.2

Chanson (1998), Saladin (1886), Schnitter (1971), Smith (1971).

Year of compl. year of completion, H dam height, Catch. area catchment area, Reserv. capac. reservoir capacity.

Conclusion

The main findings of the present review are: (1) the reservoir sedimentation has been a major problem in Australia, and (2) the Australian engineers could draw upon local and overseas experience, and from past failures. Indeed several reservoirs (Table 1) became fully silted because the designers did not take into account correctly the soil erosion and sediment transport processes, and no soil conservation practice was introduced.

Today the society expects the useful life of a reservoir to be more over 30–50 years. One lesson from past experience is the need to consider the dam, the reservoir, and the catchment as a complete system which cannot be dissociated. Soil erosion and water runoff lead into the streams some sediment material that is trapped downstream by the dam wall. A total catchment management policy must be considered from the early stage of a reservoir design.

The fully silted reservoirs stand as a source of embarrassment for the scientists and the public (Figures 2–5). Each reservoir failure must be a valuable teaching and pedagogic tool to heighten the awareness of students, professionals and local authorities, and of the public. Society must learn from its mistakes, not to repeat them again!

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Cross-references

[Australia, Climate and Lakes Reservoir Sedimentation](#)
[Xiaolangdi Reservoir's Role in Water and Sediment Regulation](#)

RESERVOIRS IN GREAT BRITAIN

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Introduction

The development of large impounding reservoirs in Britain was mainly due to the necessity of feeding the canals constructed during the first phase of the industrial revolution (1750–1850). It was not until 1868, however, that civil engineers began to carry out research on reservoir storage when the subsequent design of impounding reservoirs replaced the use of early natural lakes for water supply.

Early-nineteenth-century reservoirs almost invariably had earthen embankments with central clay puddle walls, a construction that was known and used before 1800.

Later, impounded reservoirs were formed mainly of masonry or concrete including buttress dams of mass concrete made possible by the invention of Roman cement by Dobbs in 1810 followed by Aspdin's improved patent for Portland cement. These important inventions led to the first British Standard in 1904 (BS 12). The BS stipulated clear requirements with regard to safety measures in design and improved manufacturing techniques. However, the dam disaster in Wales in 1925 led to the Reservoirs (Safety Provision) Act of 1930, which made clear the dangers to reservoirs and the necessary precautions.

Reservoirs in Great Britain, Table 1 Reservoirs: Great Britain (capacity over $10,000 \times 10^3 \text{ m}^3$)

Reservoir	Authority	Nearest town	Grid ref	Date	Dam height m	Dam length m	Reservoir capacity 10^3 m^3	Surface area 10^3 m^2
Abberton	Essex & Suffolk Water	Colchester	TL 981183	1938	15	731	25,721	4,900
Alwen (1)	Welsh Water	Denbigh	SH 955530	1916	30	122	14,564	1,490
Alwen (2)	Welsh Water	Denbigh	SH 955527	1916	4	122	14,564	1,490
Awe Barrage	Scottish Hydro Electric ^a	Oban	NN 045287	1962	13	88	256,000	39,000
Backwater	Scottish Water	Dundee	NO 253591	1969	37	550	25,000	1,820
Balderhead	Northumbrian Water	Barnard Castle	NY 928184	1964	52	914	19,684	1,169
Benevean	Scottish Hydro Electric ^a	Beaulay	NH 273276	1951	27	177	27,467	4,111
Bewl Bridge	Southern Water	Tunbridge Wells	TQ 683337	1975	31	956	31,400	3,100
Blackwater	British Alcan	Kinlochleven	NN 247605	1909	24	930	111,300	9,600
Blithfield	South Staffs Water	Rugeley	SK 060235	1953	16	856	18,172	320
Bouth Beech	Sutton & East Surrey Water	Edenbridge	TQ 494477	1969	24	1,312	10,440	295
Bwlch-y-gle	Severn-Trent Water	Llanidloes	SN 898885	1968	9	25	50,000	2,490
Caban Coch	Welsh Water	Rhayader	SN 926646	1904	44	186	35,531	2,023
Carron Valley	Scottish Water	Denny	NS 695838	1938	13	435	21,800	3,892
Carsington	Severn-Trent Water	Wirksworth	SK 245500	1992	34	1,200	35,000	2,950
Catcleugh	Scottish Water	Jedburgh	NT 747031	1905	25	558	10,500	1,072
Chew Valley Lake (Chew Stoke)	Bristol Water	Wansdyke	ST 570600	1956	13		20,457	4,857
Claerwen	Welsh Water	Rhayader	SN 869636	1952	67	355	48,307	2,630
Clatteringshaws	Scottish Power	Dumfries	NX 546753	1935	23	448	41,520	4,290
Cluanie	Scottish Hydro Electric ^a	Fort Augustus	NH 185098	1955	35	675	203,032	10,926
Clunie	Scottish Hydro Electric ^a	Pitlochry	NN 884603	1950	21	141	36,359	6,131
Clywedog	Severn-Trent Water	Llanidloes	SN 898885	1967	65	183	50,000	2,490
Col	Scottish Hydro Electric ^a	Dunoon	NS 083837	1953	8	202	12,500	1,101
Colliford Water	South West Water	Bodmin	SX 179710	1983	29	520	29,100	3,690
Covenham	Anglian Water	Louth	TF 354960	1970	15	915	10,900	882
Cow Green	Northumbrian Water	Barnard Castle	NY 812289	1970	26	572	40,915	3,116
Cruachan	Scottish Power	Oban	NN 080282	1965	46	322	11,300	485
Cruadhach North – Loch Quoich	Scottish Hydro Electric ^a	Fort Augustus	NM 932996	1956	13	146	382,800	19,222
Cruadhach South – Loch Quoich	Scottish Hydro Electric ^a	Fort Augustus	NM 932993	1956	17	87	382,800	19,222
Daer	Scottish Water	Dumfries	NS 981091	1954	42	793	25,397	2,000
Dalwhinnie	Scottish Hydro Electric ^a	Dalwhinnie	NN 633843	1937	14	354	229,367	23,269
Derwent	Northumbrian Water	Consett	NZ 025514	1966	36	975	50,000	4,050
Draycote – Barn	Severn-Trent Water	Rugby	SP 460700	1969	8	390	22,730	2,648
Draycote – Farborough	Severn-Trent Water	Rugby	SP 460700	1969	12	790	22,730	2,648
Draycote – Hensborough	Severn-Trent Water	Rugby	SP 460700	1969	8	430	22,730	2,648
Draycote – Saddle	Severn-Trent Water	Rugby	SP 460700	1969	5	210	22,730	2,648
Draycote – Toft	Severn-Trent Water	Rugby	SP 460700	1969	13	660	22,730	2,648
Draycote – Toft	Severn-Trent Water	Rugby	SP 460700	1969	13	660	22,730	2,648
Draycote – Main Dam	Severn-Trent Water	Rugby	SP 460700	1969	21	1,372	22,730	2,648
Ericht	Scottish Hydro Electric ^a	Pitlochry	NN 508627	1938	14	404	229,367	23,269
Fannich	Scottish Hydro Electric ^a	Dingwall	NH 263660	1957	8	744	362,000	10,967

Reservoirs in Great Britain, Table 1 (Continued)

Reservoir	Authority	Nearest town	Grid ref	Date	Dam height m	Dam length m	Reservoir capacity 10 ³ m ³	Surface area 10 ³ m ²
Foremark	Severn-Trent Water	Burton-upon-Trent	SK 329244	1977	35	1,036	13,193	930
Fruid	Scottish Water	Peebles	NT 088205	1974	23	305	10,900	1,190
Garthbeg (cut-off dam)	Scottish Hydro Electric ^a	Inverness	NH 517175	1972	3		14,500	4,280
Garthbeg (embankment)	Scottish Hydro Electric ^a	Inverness	NH 516171	1896	5		14,500	4,280
Gaur	Scottish Hydro Electric ^a	Pitlochry	NN 461568	1954	13	111	10,194	1,546
Giorra	Scottish Hydro Electric ^a	Aberfeldy	NN 507420	1959	30	463	42,840	2,906
Glascarnoch	Scottish Hydro Electric ^a	Dingwall	NH 345707	1957	30	534	77,900	10,900
Glen Finglas	Scottish Water	Callander	NN 530078	1965	36	229	19,018	1,400
Grafham Water	Anglian Water	Bedford	TL 170670	1964	25	1,707	57,760	6,281
Graphs		Claverdon	SP 170671	1964	23		6,000	
Grimwith	Yorkshire Water	Pateley Bridge	SE 060642	1983	49	994	21,772	1,470
Gyfyfynys	Nuclear Electric	Maentwrog		1928	12	357	32,668	
Hanningfield	Essex & Suffolk Water Company	Chelmsford	TQ 733984	1958	18	2,133	27,721	3,538
Haweswater	United Utilities	Penrith	NY 500155	1940	33	472	84,839	3,945
Hendrerumur	Nuclear Electric	Trawsfynydd		1928	5	219	32,668	
Hollins Wood				1960	4		60,000	
Invergarry	Scottish Hydro Electric ^a	Fort Augustus	NH 276021	1956	13	47	38,000	6,920
Kielder	Northumbrian Water	Newcastle-upon-Tyne	NY 708875	1982	55	1,140	200,000	10,860
King George V	Thames Water	Chingford	TQ 374965	1912	8	6,540	12,400	1,720
King George VI	Thames Water	Staines	TQ 041732	1947	17	5,263	20,300	1,416
Ladybower	Severn-Trent Water	Hathersage	SK 200855	1945	43	363	27,800	2,040
Laggan	British Alcan	Fort William	NN 373808	1936	40	213	39,640	10,300
Lawers	Scottish Hydro Electric ^a	Killin	NN 599392	1958	38	344	13,050	753
Lednock	Scottish Hydro Electric ^a	Crieff	NN 728288	1958	33	290	30,073	1,671
Little Loch Shin (diversion)	Scottish Hydro Electric ^a	Lairg	NC 582051	1960	9	135	25,000	370
Llandegfedd	Welsh Water	Pontypool	ST 326985	1963	39	351	24,408	1,732
Llyn Brenig	Welsh Water	Denbigh	SH 977543	1976	50	1,200	61,500	3,715
Llyn Brianne	Welsh Water	Llandovery	SN 791485	1972	91	274	61,000	2,096
Llyn Celyn	Welsh Water	Bala	SH 860401	1965	58	701	73,965	3,500
Llyn Tegid (Bala Lake)	Environment Agency	Bala	SH 929350	1959	4		18,400	
Loch Arklet	Scottish Water	Stronachlachar	NN 356094	1914	8		12,284	
Loch Badanloch	Helmsdale Fisheries Board	Kinbrace	NC 789332	1972	2	120	20,455	8,900
Loch Bradan	Scottish Water	Ayr	NX 435994	1973	31	438	19,200	2,110
Loch Calder	Scottish Water	Thurso	ND 085595	1963	4	80	12,956	3,800
Loch Doon	Scottish Power	Ayr	NS 478015	1936	14	299	82,969	429
Loch Earn	Scottish Hydro Electric ^a	Crieff	NN 699242	1957	7	15	34,100	9,900
Loch Glashan	Scottish Hydro Electric ^a	Inveraray	NR 920926	1961	20	378	21,175	1,940
Loch Hempriggs	Scottish Hydro Electric ^a	Wick	ND 348472	1826	1		30,000	875
Loch Katrine	Scottish Water	Callander	NN 490068	1859	10		64,610	
Loch Ken	S.S.E.B.	Castle Douglas	NX 641757	1934	11		40,840	12,340
Loch Lochy – Gairloch	British Waterways Board	Fort William	NN 233901	1846	8		51,652	17,596

Reservoirs in Great Britain, Table 1 (Continued)

Reservoir	Authority	Nearest town	Grid ref	Date	Dam height m	Dam length m	Reservoir capacity 10 ³ m ³	Surface area 10 ³ m ²
Loch Lomond	Scottish Water	Dumbarton	NS 393815	1971	2		86,400	7,100
Loch Mhor	Scottish Hydro Electric ^a	Inverness	NH 514182	1896	7		14,500	4,280
Loch Monar – Monar	Scottish Hydro Electric ^a	Beaully	NH 203393	1963	35	161	174,100	74,677
Loch Morar	Scottish Hydro Electric ^a	Mallaig	NM 684923	1948	3	16	46,000	28,800
Loch Shin (Main dam)	Scottish Hydro Electric ^a	Lairg	NC 575070	1957	32	448	318,000	32,500
Loch Sloy	Scottish Hydro Electric ^a	Dumbarton	NN 288112	1951	49	357	35,679	1,331
Loch Thom	Scottish Water	Greenock	NS 252729	1827	20	427	10,748	1,576
Loch Turret	Scottish Water	Crieff	NN 820265	1964	24	335	18,100	1,840
Loch Venacher	Scottish Water	Callander	NN 598066	1859	5		11,765	
Loichel	Scottish Hydro Electric ^a	Beaully	NH 199388	1962	14	170	174,100	74,677
Loyne	Scottish Hydro Electric ^a	Fort Augustus	NH 201079	1956	18	549	45,500	6,151
Lubreoch	Scottish Hydro Electric ^a	Aberfeldy	NN 452417	1958	33	530	83,200	5,040
Luichart	Scottish Hydro Electric ^a	Dingwall	NH 388580	1954	16	219	62,000	6,640
Maentwrog	Nuclear Electric	Maentwrog	SH 673377	1991	40	305	32,668	
Megget	Scottish Water	Selkirk	NT 211229	1982	56	568	61,400	2,560
Mucomir Barrage	Scottish Hydro Electric ^a	Fort William	NN 183839	1962	3	35	46,300	17,500
Mullardoch	Scottish Hydro Electric ^a	Beaully	NH 222313	1951	37	727	223,000	9,410
Nant	Scottish Hydro Electric ^a	Oban	NN 003249	1962	23	372	27,700	2,270
Nant-y-Moch	PowerGen	Ponterwyd	SN 754862	1962	56	350	32,564	2,630
Orrin	Scottish Hydro Electric ^a	Dingwall	NH 403504	1959	45	312	59,466	4,180
Orrin (embankment)	Scottish Hydro Electric ^a	Dingwall	NH 397498	1959	25	312	59,466	4,180
Pitsford	Anglian Water	Northampton	SP 755689	1956	26	521	17,545	3,034
Pontsticill	Welsh Water	Pontsticill	SO 061119	1927	34	320	15,640	1,412
Quoich	Scottish Hydro Electric ^a	Fort Augustus	NH 070023	1956	39	320	382,800	19,222
Randieford	Scottish Water	Denny	NS 675868	1938	11	475	21,800	3,892
Rannoch Weir	Scottish Hydro Electric ^a	Pitlochry	NN 660584	1933	6	207	64,000	19,260
Roadford	South West Water	Launceston	SX 420900	1989	44	430	37,000	3,000
Rutland Water (Empingham)	Anglian Water	Stamford	SK 944080	1975	40	1,200	124,000	12,600
Scar House	Yorkshire Water	Pateley	SE 058769	1936	71	482	10,069	700
Selset	Northumbrian Water	Barnard Castle	NY918211	1959	41	928	15,320	1,113
Shira Main	Scottish Hydro Electric ^a	Inveraray	NN 164202	1959	41	725	22,500	1,440
Stocks	United Utilities Water	Slaidburn	SD 720546	1932	31	354	12,006	1,390
Taf Fechan (Pontsticill)	Welsh Water	Merthyr Tydfil	SO 061118	1927	33	308	15,461	1,412
Talla	Scottish Water	Peebles	NT 106229	1905	24	320	12,728	1,210
Talybont	Welsh Water	Brecon	SO 106205	1939	30	427	11,668	1,272
Tarsan	Scottish Hydro Electric ^a	Dunoon	NS 070833	1953	22	344	12,500	1,101
Thames barrier	Environment Agency	London		1983	32	520	44,000	10,000

Reservoirs in Great Britain, Table 1 (Continued)

Reservoir	Authority	Nearest town	Grid ref	Date	Dam height m	Dam length m	Reservoir capacity 10 ³ m ³	Surface area 10 ³ m ²
Thirlmere	United Utilities Water	Keswick	NY 310190	1894	20	224	40,714	3,290
Trawsfynydd	Nuclear Electric	Trawsfynydd	SH 703365	1928	6	787	32,668	4,775
Treig	British Alcan	Fort William	NN 348772	1934	12	116	76,600	7,300
Usk	Welsh Water	Brecon	SN 833288	1955	33	480	12,253	1,160
Vaich	Scottish Hydro Electric ^a	Dingwall	NH 346749	1957	29	257	11,213	1,518
Vyrnwy	Severn-Trent Water	Welshpool	SJ 018193	1892	26	335	59,700	4,536
Whitehill Flood Storage Area	Thames Water	Swindon	SU 126854	1982	1	400	47,412	62
William Girling	Thames Water	Chingford	TQ 367941	1951	13	5,660	13,500	1,350
Wimbleball	South West Water	Tiverton	SS 967293	1978	63	300	21,500	1,620
Wraysbury	Thames Water	Spelthorne	TQ 025745	1970	16	5,700	34,550	2,023

After Register of British Dams, Building Research Establishment report. Tedd P, Holton I.R. and Charles J.A. 1992 Acknowledgement is made to BRE for permission to publish these tables.

^aNow Scottish and Southern Electric

Afforestation of catchments started at Oldham in 1885 and has now developed on scientific principles so that today the aesthetic treatment of reservoir catchments is given due consideration in the overall construction of the reservoir.

The record of notable events, improvements, research, and Royal Commissions in the field of reservoirs and water engineering practice in Britain could be said to have extended through nine monarchies: George III (1760–1820), George IV (1820–1830), William IV (1830–1837), Victoria (1837–1901), Edward VII (1901–1910), George V (1910–1936), Edward VIII (1936), George VI (1936–1952), and Elizabeth (1952–present).

Given in the following table are the major reservoirs in operation in Britain (2011) (Table 1).

Cross-references

[Large Dams, Statistics and Critical Review](#)
[Reservoirs, Early British History](#)

RESERVOIRS, EARLY BRITISH HISTORY

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Design

Impounding reservoirs in Britain were first introduced during the Industrial Revolution at the end of the eighteenth century for feeding the canals. Reservoirs for public water supplies were constructed early in the nineteenth century, an example being the City of Manchester scheme in the Longendale Valley comprising of seven reservoirs having a gross yield of 150 m³ per day. The construction of these reservoirs was carried out between 1848 and

1877, and the civil engineer was La Trobe Bateman who also designed the Loch Katrine scheme opened in 1859 by Queen Victoria. The Loch Katrine scheme required 70 distinct tunnels over a 34-mile aqueduct to take the water to Glasgow upon which some 44 vertical shafts were sunk for facilitating and expediting the completion of the work. Loch Katrine is a natural loch with drainage area of some 9,393 ha and surface area of 1,315 ha.

The earliest reservoirs were normally formed of dams with a central puddle clay core and shoulders of selected fill. Dam construction has always been a developing civil engineering experience, and today the design of reservoirs is not significantly different from the early days although much has been learned from failures and from the study of soil mechanics. The principal development of earth dams and construction from the middle of the nineteenth century have included the use of concrete for filling cutoff trenches, cement grouting for sealing leaks, dewatering techniques, and modern earth moving plant (Skeat, 1969).

Between 1796 and 1850, 28 earth dams over 15 m high were built for water supply in the British Isles and 141 between 1850 and 1900, three of which were concrete gravity dams. Today, there are some 1,300 dams in the British Isles of which some 90 are hydroelectric supply dams.

Some dam failures have occurred, the more important ones being at Dale Dyke and Dolgarrog. In 1864, the former earth dam for Sheffield failed with the loss of 244 lives. The latter failure was in 1925 with the loss of 16 lives. As a result, the Reservoirs Safety Law of 1930 provided for all reservoirs containing more than 22,700 m³ (5 mg) required a civil engineer appointed by the Government to supervise the design and construction. All reservoirs have to be inspected at least once every 10 years.

Reservoir capacity and yield design rules were first introduced by Hawksley in 1868 and Deacon in 1902 with

further development by Lapworth in 1949, but later as runoff records became available, reservoir design has been based on these records rather on rules. Today has seen examples of river regulation reservoirs where storage is used to augment the river flow at an abstraction point lower down the river. In addition, pumped storage reservoirs have been constructed mainly in the 1970s and 1980s where the direct runoff is augmented by water pumped into the reservoir. The next stage of reservoir development might be estuarial barrages where the whole catchment area is utilized. Such schemes have been proposed for the Wash, the Solway Firth, and Morecambe Bay.

Water treatment

Sand filtration

The treatment of reservoir water by sand filtration was first researched by James Peacock in 1791 and introduced in Paisley by John Gibb in 1804 and Robert Thom at Greenock in 1827. Sand filtration of various types was employed throughout Britain, and in 1940 and 1942, experiments were carried out in Kilmarnock by P.L. Boucher on microstrainers which were then introduced by Glenfield and Kennedy in 1945.

Chlorine

Following the experiments by the reading water engineer Leslie Walker in 1908, in collaboration with the Candy Filter Company, the Reading Corporation installed a full-scale chlorination plant for the treatment of the public supply in 1910, thus becoming the first water undertaking in the country to adopt chlorination as a routine measure (Skeat, 1969).

Coagulation

Coagulation of water with sulfate of alumina began experimentally in 1827 and was used in Bolton for the first time in 1881. Sodium aluminate was introduced from the United States in 1924, and activated silica introduced as a coagulant aid by J.R. Baylis in the United States was first used on a large scale by Warrington Corporation in 1947. Activated carbon is now in general use as a purifying agent for water as a taste remover.

Disinfection

Disinfection by excess lime was first considered by Thomas Clark in 1841, and in conjunction with Sir William Paterson and Sir Alexander Houston, a plant was installed of 31,780 m³/day at Southend Waterworks.

Ozone

Ozone came into Britain from France in 1936, and plants were established at South Staffordshire Water Works Company and Brighten Corporation.

Fluoride

In 1892, Sir James Crichton-Browne concluded that he found some connection between fluoride in the diet and dental caries. However, it was not until 1946 when

fluoride was introduced in the United States that British water engineers decided to consider it for reducing the incidence of dental caries. There was considerable public opposition, however, and today only a minority of water companies have introduced fluoride to the supply.

Softening

About 50% of the British water supply is considered "hard." Experimentation on softening water was carried out by Ruttie (1698–1775), Home (1719–1813), and Henry (1734–1816), but no plants were built until 1841. Thomas Clark (1801–1867) was granted a patent which allowed for the removal of temporary hardness only, but the idea of softening was not favored by the population and even today only a minority of water companies soften the supply. The first softening plant was installed in Plumstead in 1854.

Waterborne diseases in reservoirs

The following diseases associated with water are:

Cholera
Dysentery (bacillary and amoebic)
Gastroenteritis
Paratyphoid
Typhoid
Weil's disease (Leptospirosis).

Examples Epidemics from waterborne diseases not only in Britain but in other countries are:

- London, 1853–1854, outbreaks of cholera 616 deaths – polluted River Thames source untreated.
- Grimsby, Cleethorpes, and Ashbourne, cholera 287 cases and 135 deaths.
- Hamburg, 1892, polluted River Elbe source – cholera, 8,000 deaths.
- Lincoln, 1904, polluted River Witham source – typhoid fever.
- Malton, 1932, polluted well source – typhoid, 23 deaths.
- Chicago, 1933, contamination in the distribution system – dysentery, 1,409 cases, 98 deaths.
- Croydon, 1937, polluted well source – typhoid.
- Huskerville (Lincoln) Nebraska, 1952, poliomyelitis – 20 paralytic cases, 2 deaths.
- Delhi, 1955, hepatitis, polluted River Jumna source – 29,300 cases of jaundice.
- Zermatt, 1963, springs and river sources, typhoid, 437 cases.
- Hong Kong, 1964, well – cholera, 17 cases, 4 deaths.
- Other cases included cholera in Egypt in 1947 in Bengal and Southeast Asia in 1961, and in 1965, cholera spread across the Asiatic region of the former USSR and Iran where 2,943 cases occurred.

It will be noted that most of the above sources were from rivers and wells. Pathogenic bacteria such as *Escherichia coli* do not usually survive in water in reservoirs for more than 30 days. Reservoirs therefore perform

the first stage of treatment and afford dilution and retention of the supply. Reduction of the organic matter takes place by the biochemical oxidation, and physical quality may increase from sedimentation of suspended matter.

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Skeat, W. O., 1969. *Manual of British Water Engineering Practice*. Cambridge: The Institution of Water Engineers/W. Heffer & Sons.

Cross-references

[Reservoirs in Great Britain](#)

RESERVOIRS, MULTIPURPOSE USE OF SMALL RESERVOIRS

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Flood-flow harvesting and small reservoirs

Since ancient times, flood-flow harvesting from valleys, gullies, temporary streams, and its storage in pans, ponds, or small dams have allowed men to manage multipurpose reservoirs. Pans and ponds are dug up to capture and store runoff from surfaces such as hillsides, rocky areas, or rangelands (Mati et al., 2005).

When catchment areas are appropriate and the sedimentation basin is impervious enough, pans and ponds can collect enough water for rural needs such as watering cattle and irrigating crops. Mati et al. 2005, show that a well-designed network of small farm pounds with a good density can improve rural livelihoods by improving food and water security in Sub-Saharan Africa (Figure 1).

However, pans and ponds remain precarious structures because of their small size and risk of drying up, especially in arid climate. Subject to evaporation and to seepage, water in pans and ponds needs to be renewed very often. To control seepage, ponds can be lined with special plastics which dramatically increase their cost. They are also very susceptible to siltation when the rate of erosion is high in catchment areas. In this case, they require frequent maintenance and dredging. They are also subject to destruction when they are overflowed.

Small dams are the more popular method of water harvesting, especially from temporary streams (Figure 2). The dykes of these dams are between 3 m and 15 m high (lowest limit for large dams established by the International Commission on Large Dams). They are built across a stream to form a reservoir in the valley. They are built with earth, stones, or concrete, and located in small rural upper catchments. Small dams have rustically designed lateral spillways with a discharge capacity of some tens of cubic meters per second or even, in some cases, just over 100 m³/s. Some, but not all, have a sluice gate and their unit cost is around 500,000 Euros, sometimes far less. Their reservoirs are relatively small in area

(a few hectares) and have a holding capacity ranging from a few tens of thousands to one million cubic meters (Albergel and Rejeb, 1997). A small dam can be constructed to collect water from few square kilometers (1–10 km²) for a steep catchment to 100 km² for a flat one.

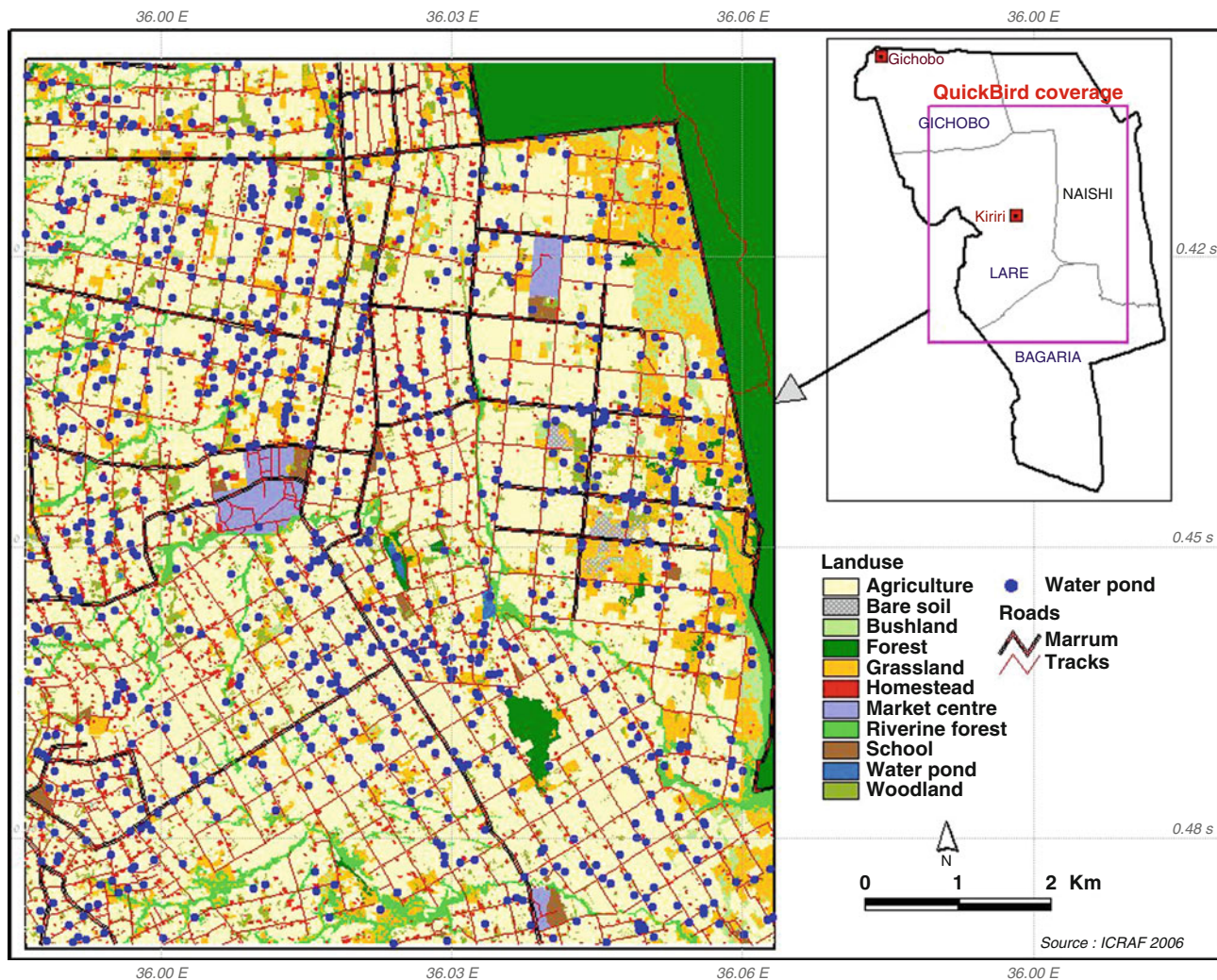
Small dams have been built since the early hydraulic civilizations, Ancient Egypt, Sri Lanka, Mesopotamia, China, and The Roman Empire. In Syria, the dam on the Nahr El Asi near Homs was constructed during the reign of Seti I (1319–1304 B.C.). Many were built at the start of the Christian era (Badieh Dam on the road to Palmyra) (Figure 3). Numerous ruins testify to their presence in the dry steppes. Some still exist but are completely filled with sediment.

In modern times and especially since the second half of the twentieth century, small dams were constructed all around the world, particularly in semi-arid areas. They are often the only possibility to promote development in mountainous (semi-) arid regions. Most of these small reservoirs have multiple uses, including drinking water, fishing, watering livestock, and irrigation of crops. Besides the economic benefits of irrigation and maintenance of livestock, improved access to water promotes health through better nutrition, increased hygiene and reduction of diseases caused by poor hygiene, such as skin infections and eye diseases. Since the 1980s, small dams have been built to protect bigger dams downstream from siltation.

Nowadays, small dams are an important component of landscapes in tropical and mediterranean areas. Their number continues to increase. Numerous and dispersed in the landscape, they structure the rural landscapes and, generate diverse resources. They induce a juxtaposition of often complementary, sometimes competing, and possibly antagonistic actors and practices. They lead to changes in social and institutional rearrangements by new rules on access to resources and ecosystems (Cecchi, 2007).

To assess the benefits and risks associated with these structures, several scientific studies emerged in the late 1990s and early 2000s. These studies, concerned with sustainable development of rural areas, lead to a more general reflection on the ecological and social changes associated with the development of the valleys.

In many tropical and mediterranean countries, studies of the impact of small dams showed positive and negative effects on human health, environment, and socioeconomic development. In some areas, dams have accelerated socioeconomic development (Egziabher, 2003, Albergel et al., 2004a), but other dams have been abandoned because of their deleterious effects on the environment, including erosion, sedimentation (Albergel et al., 2005), and salinization (Laraque, 1991). Many small dams have been installed throughout the world to supply drinking water in rural areas or small towns, especially in areas without groundwater resources (Albergel et al. 2004b). Cyanobacteria are very common in many eutrophic reservoirs and are known to contribute by their blooms to the deterioration in the quality of water (Bouvy et al., 1999).



Reservoirs, Multipurpose Use of Small Reservoirs, Figure 1 Distribution of 908 ponds in Lare Division, Nakuru Kenya (in Mati et al., 2005).

In northern Ethiopia, the construction of small dams has resulted in increased transmission of malaria and bilharzia (Alemayehu et al., 1998; Ghebreyesus et al., 1999). The impact of dams on malaria was far less clear because *Anopheles* is found mainly in the hoof prints of cattle near the tanks, rather than in dams and their infrastructure (Cecchi, 2007).

Small reservoirs: water mobilization for local development function

Runoffs that fill small dams are sometimes generated by a single rainfall event. This event can occur outside the rainy season. Often, the high rate of evaporation from the lakes, together with their shallowness, does not allow the water to be kept for long. Moreover, the submerged banks are often permeable and significant infiltration occurs. Figure 4 shows, for Syndiane Dam in Syria near the city of Homs: (1) the daily precipitation, (2) the levels

of the water in the dam, and (3) the level of siltation. The spillway level and that of the top of the dyke are indicated, making it possible to highlight the discharges. Note the low storage level in 1999, a very dry year throughout the Middle East.

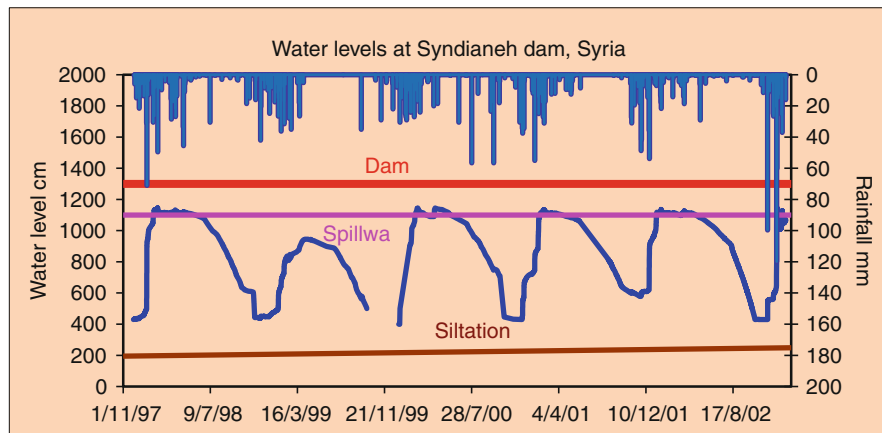
The temporarily stored water can be used in a number of ways. In pastoral areas, small dams provide the water for cattle transhumance. In cultivated areas, they provide water for irrigation, or downstream of the dam, by gravity, or in plots on the banks of the dam by pumping or by using recharge of soil moisture on the banks when the water recedes during the dry season. This cropping system based on the recession of the reservoirs is very common in northeastern Brazil and is called “Vazante” near the “Acudes,” a Brazilian name for small dams. An analysis of the agricultural production systems around 26 hill reservoirs in Tunisia, conducted between 1993 and 1996, gave an understanding of the dynamics of agricultural



Reservoirs, Multipurpose Use of Small Reservoirs, Figure 2 Small reservoir Western Rif (Morocco).



Reservoirs, Multipurpose Use of Small Reservoirs, Figure 3 Roman Dam of Dadieh, road Homs – Palmyra.



Reservoirs, Multipurpose Use of Small Reservoirs, Figure 4 Levels of water in Syndianeh Dam (Syria).

development. It showed that just after the building of the dam (Selmi, 1996):

- 50% of the farmers had not introduced irrigation and were maintaining their traditional system of production.
- 28% were starting to integrate into their system of agricultural production.
- 22% of the farmers currently used small-scale irrigation.

The availability of this water opens the door to new and very profitable speculative activities (in particular, market gardening and fruit-growing) with a gross profit margin up to ten times as high as that of traditional extensive cereal-growing. This optimum use of the water from the hill reservoirs is a source of major additional income, reflected in better living conditions and speculation in land adjacent to the reservoirs.

However, the rapid siltation of some reservoirs has disappointed the farmers. Thus, eight hectares of apple trees planted in the first 3 years of existence of the Sadine reservoir (upper catchment of the Zeroud in Tunisia) are today suffering due to lack of water and at present, are not very productive. 90% of the reservoir's capacity is in fact lost to sedimentation after 20 years.

As the interannual stocks of water held in these storage reservoirs are extremely variable, the idea has been to use them to recharge the phreatic water tables. In Tunisia, Montoroi et al., 2002 provide geochemical evidence of efficient recharge of the alluvial water table by the small dam, and explain the recharge mechanism by the strong infiltrations when the dam is flooded and the water reaches the permeable alluvial terraces. The dam forces the natural system of recharge of the alluvial water tables in the semi-arid zones. Recharge occurs mainly through inundation of the main beds of the waddis.

When climate and hydrology allow permanent impoundment of the reservoir, fishing becomes an important activity for communities bordering the small dams. The fishing effort and the fish production in small dams

of North Ivory Coast represent from 16% to 46% of total freshwater catches (Dacosta et al., 1998). Catches include economically important fish (*Oreochromis niloticus*, *Heterotis niloticus*, *Chrysichthys* spp., etc.) and marketing values indicate that the fishing activity is an important source of currency for the villages.

The first small dams built using modern techniques in Syria were those constructed during the 1960s in the province of Swaida to supply drinking water to villages on a basalt plateau that has no underground water resources. To supply drinking water, the infrastructure needs to be medium sized, with a permanent impoundment and should be well protected from diffuse and accidental pollutions. Nevertheless, a serious monitoring of plankton and water quality must be performed to prevent supply to drinking water faucets during cyanobacterial bloom. In 1996, a cyanobacterial bloom occurred in the water supply for a hemodialysis center in Caruaru (Brazil). Despite extensive pretreatment (sand, carbon, resin and microfiltration), more than 117 of 136 patients (86%) experienced symptoms, and 75 patients (55%) died from the incident.

Other socioeconomic benefits of small reservoir projects are tourism, infrastructure development, employment opportunities, alleviation of poverty, and improved living conditions. Near large towns, there are holiday homes at the sites of small dams and the lakes are used for leisure activities. Such is the case with the small dam at Al Corane, not far from Damascus in a small high valley with cool weather in summer time.

Small reservoirs: erosion control and infrastructure protection function

North African countries developed a large hydraulic infrastructure in the 1970s and 1980s. Almost all the large dams are affected by significant sediment. Numerous small dams have been built to slow down siltation of the largest downstream reservoirs. The idea is to capture sediment, which is essentially produced by upstream sloppy zones, in small and relatively inexpensive reservoirs.

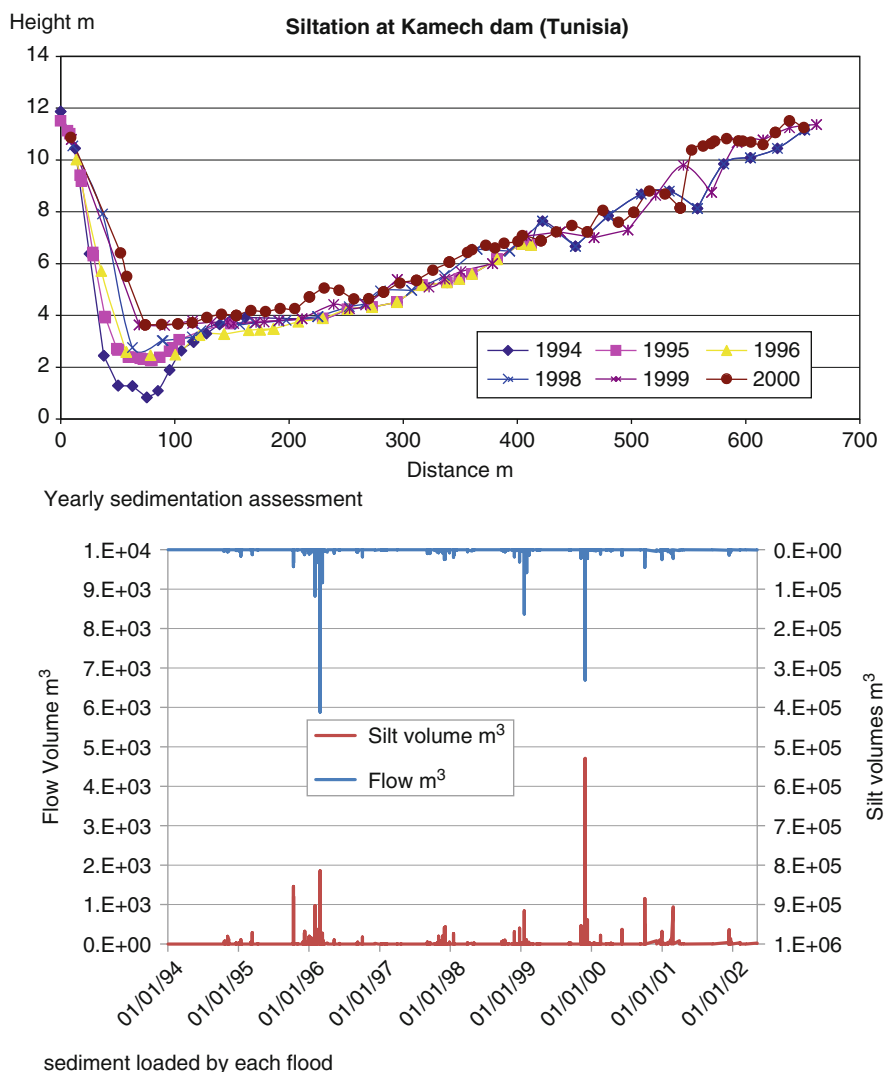
The construction of small dams at different points of the hydrological network attenuates the flood wave and reduces the erosion dynamics of the runoffs.

For example, the largest dam in Morocco, the Al Wahda Dam on the Ouergha River in the province of Sidi Kacem (88 m high, with a capacity of $3.4 \cdot 10^9 \text{ m}^3$), is protected by many small dams in the upstream catchment designed to hold the erosion coming from the steep marly slopes of the Rif. Some have already been constructed, while others are planned. Erosion from the Ouergha catchment, estimated at 98 tones ha^{-1} annually over 6150 km^2 , causes the dam to lose a volume of $60 \cdot 10^6 \text{ m}^3$ each year (IAASTD, 2008).

An assessment of siltation of 26 small reservoirs was performed in the mediterranean countries during the HYDROMED program (1996–2000) (Albergel and Nasri, 2001). Siltation relative to the area of small dam

catchment ranges from $1.1 \text{ m}^3/\text{ha}/\text{year}$ (or $1.8 \text{ t}/\text{ha}/\text{year}$), for a fairly wooded piedmont catchment where a lot of erosion control work has been done (El Gouazine in Central Tunisia), to $31 \text{ m}^3/\text{ha}/\text{year}$ (or $50 \text{ t}/\text{ha}/\text{year}$) for a small, very marly catchment in the pre-Rif hills of Morocco: the Saboun Dam.

A hydrological model to reconstitute the solid transport for each flood event was performed. It provided a better understanding of the erosion and of its consequences on the siltation of the reservoirs of small dams. Figure 5 shows the results of this model for Kamech Dam in Tunisia. It can be seen that siltation is associated with extreme events. Three floods were responsible for 50% of the solid transport over a 9-year period of observation (27 February 1996, 18 January 1999 and 29 November 1999). The last contributed to 20% of the sediment transport noted over the period (Albergel et al., 2004a, b).



Reservoirs, Multipurpose Use of Small Reservoirs, Figure 5 Model to simulate sediment transport flood by flood, Kamech Tunisia.

Small reservoirs: environmental impacts

Environmental impacts of large dams are well studied and quantifiable, while small dams have generally been perceived as benign, and their environmental impacts are rarely the subject of extensive studies.

The oases effect of small dams in dry areas is often quoted as the more positive environmental impact of small reservoirs. The aquatic vegetation that grows in the reservoirs provides a suitable habitat for wetland fauna (batrachians, water snakes, water tortoises, and shellfish).

The banks of reservoirs, often replanted with trees, are nesting and protection sites for birds. The Fuligule Nyroca, a rare species in North Africa and included in the list of protected species in Tunisia, nests at the hill reservoir at Cherichira (Central Tunisia). (Azafzaf and Hamrouni, 2002).

Small reservoirs, and their multiplication in the landscapes, also have significant adverse effects in particular the accumulation of sediments, salinization in some cases, and they increase the transmission of waterborne diseases, such as bilharzia, malaria, and diarrhea. Planning, construction, and rehabilitation of small reservoirs are usually done by communities and there are no systematic assessments of their impact on health and environment.

The environmental risks most often mentioned for dams are the consequences of dam failures. Despite their low load, small dams have a mean failure rate of the same order as for large dams. As there are at least 50 times as many small dams as large ones, a few dozen small dams are destroyed each year (Lemprière, 1993). When the dam has a storage capacity of 50,000 m³, its destruction goes unnoticed. It causes few disasters downstream, even though from the point of view of solid transport, the sediment stocked in the reservoir is released into the water system, and the erosion dynamics resume. When the dam is 10 m to 15 m high, with a storage capacity of a few hundred thousand cubic meters, its failure can create dangerous floods of several hundred cubic meters per second. As a large number of people may have set up homes since the dam was constructed, the dam failure can be catastrophic.

Conclusions

Small dams are structures that have their own characteristics and that can supplement a policy of water resource mobilization. They have an important role in the development of agricultural land and are the focal points for local agricultural development. Rapid silting of the reservoirs acts as a brake on agricultural development.

Storage reservoirs are good sediment traps. They protect downstream infrastructures and can prolong the life of a larger dam located downstream. Recharging the alluvial water table is in many cases a realistic objective, but an appropriate dam site must be chosen.

From an environmental point of view, the impacts are positive. They create small wetland areas, contributing to biological diversity and the protection of birds and other animals. The major environmental risk is dam failure.

The choice of location of a small reservoir must be consistent with precise objectives that are either of conservation and downstream protection or deliberately oriented toward development. In the first case, the conservation objective must be clearly defined. For instance, to protect a large dam, a certain number of reservoirs are required upstream. They have a limited life expectancy, but when they are completely silted, they will serve as small deltas to spread the water and attenuate the flood waves. During the lifetime of the structure, it is possible to plan for afforestation which only requires irrigation the first 3 years. The cost of a small dam to provide water to young trees is comparable to that of transporting the water by tanker.

With the development objective, the sustainability of the resource is the main priority, and erosion control work not affecting the water inputs should be carried out on the slopes as soon as the small dam is built. Water management then introduces the issues of liability, shared rights, and shared responsibilities for the maintenance of a collectively owned, renewable natural resource.

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Cross-references

[Health Aspects of Lakes and Reservoirs](#)
[Urban Lakes and Ponds](#)

RESTORATION OF URBAN LAKES IN THE NE MUSI BASIN, HYDERABAD, INDIA

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Lakes in NE Musi basin

Hyderabad Urban Development Authority under Green Hyderabad Program has plans to restore about 85 urban lakes in Hyderabad. As a first step, they have identified five lakes for assessing the groundwater–lake water interaction for design of sewerage treatment plants (STP). Among the six lakes in NE Musi basin around Hyderabad, viz, Patelcheruvu, Peddacheruvu, Nallacheruvu, RK Puram Cheruvu, Nadimicheruvu (Safilguda), and Bandacheruvu lakes, an STP is already functioning at Nadimicheruvu. The watershed covers an area of about 38 km² (Figure 1).

Urban lake water restoration methodology

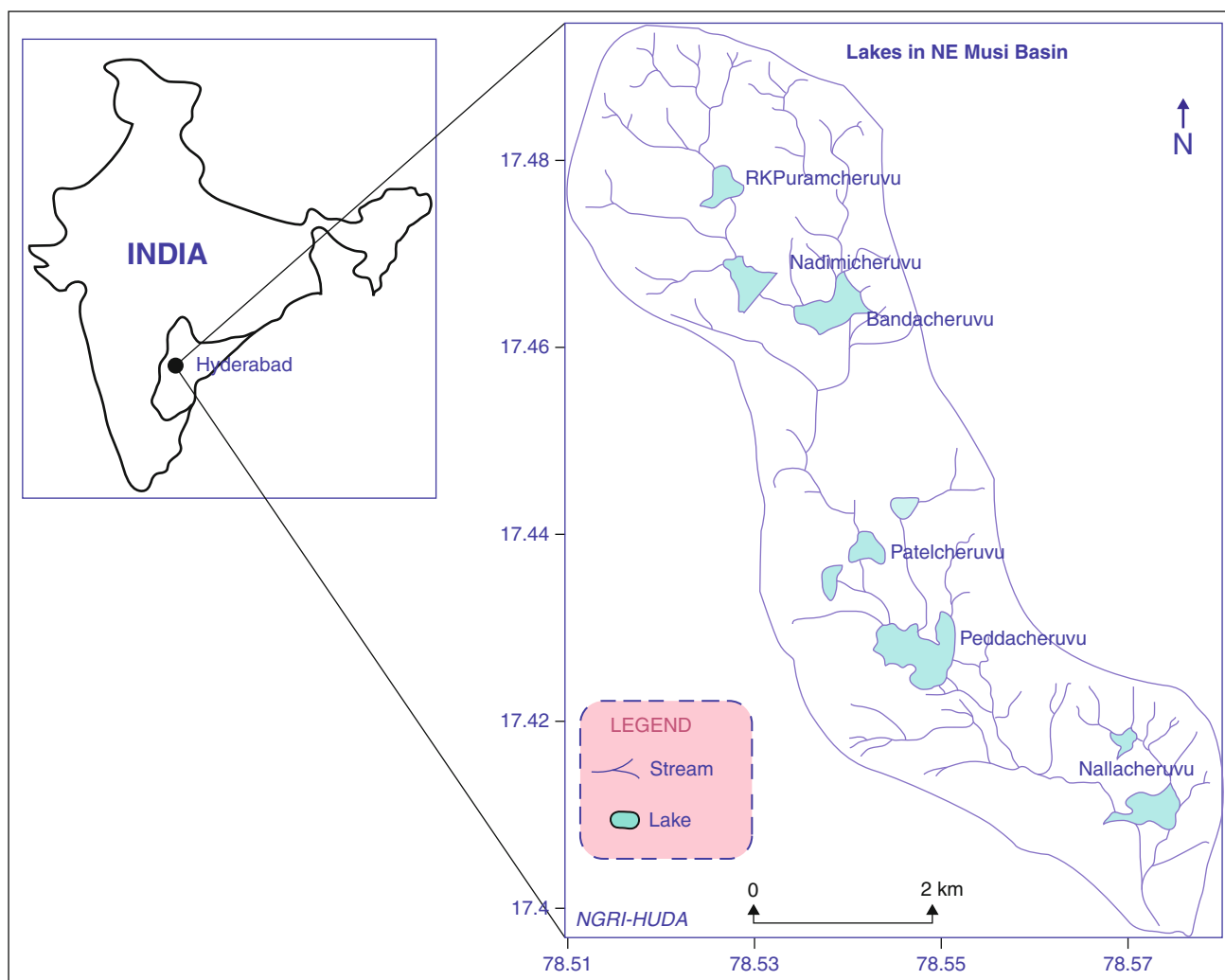
Among the parameters of interest for understanding lake water quality are biochemical oxygen demand (BOD) and chemical oxygen demand (COD), dissolved oxygen (DO), total nitrogen (TN), and total phosphorous (TP). Periodical measurements of lake water are important to characterize the changing water quality with respect to inflows as a result of monsoon and non-monsoon periods. The characterization helps to compute the status of lake in terms of nutrient load whether a lake is pristine (oligotrophic) or eutrophic. The nutrient parameters TN and TP are useful for the computation of trophic status index (TSI), and further, the status decides which is the limiting parameter for eutrophic status in the lake (Carlson, 1977). The sediments also show adsorbing capacity of nutrients, which has to be estimated through monitoring of sediment samples for nutrient status. The sediment status decides the need for dredging of lake bed for removal of phosphates as the remediation of phosphate in lake environment is through only sediment disposal.

Further, a bathymetric survey of lake bottom surface will help computation of lake storage capacity. Bimonthly monitoring of inflow and outflow measurements on the inlet and outlet channels of lake helps compute the lake residence time, which is an important parameter for taking up lake cleaning operations. The residence time decides how much time is needed for cleanup of a lake. The measurement of evaporation loss from the lake surface determines the potential loss. In addition, an important component in lake water budget is the groundwater component. The groundwater component plays a vital role, depending on the position of a lake in the watershed, namely, recharge area or discharge area.

For understanding the lake water and groundwater interaction, a groundwater flow model based on physical framework, hydrogeological parameters, inflows/outflows into lakes, height of lake water column, and groundwater withdrawal within the watershed has to be estimated. A groundwater balance has to be computed through the zone budget from the model after calibration (Gurunadha Rao et al., 2004). Further, if likely contamination from the lake is expected, a prognostic scenario depicting source loading in the lake water as well as other activities has to be incorporated in the mass transport model. The contamination of nitrates from the lake water in a watershed helps arresting spread of contamination. Lakes in NE Musi basin study have been illustrated to explain the need for a comprehensive study for lake restoration programs in the urban environment.

Water quality of lakes in NE Musi basin

The surface water quality measurements carried out in all the six lakes (Figure 1) indicate that the BOD concentration in surface water of six lakes is varying from 10 to 70 mg/L during October 2002 and 2003 – 38–169 mg/L during June of 2003 and 2004. The maximum BOD has been found in Peddacheruvu and Nallacheruvu lakes and



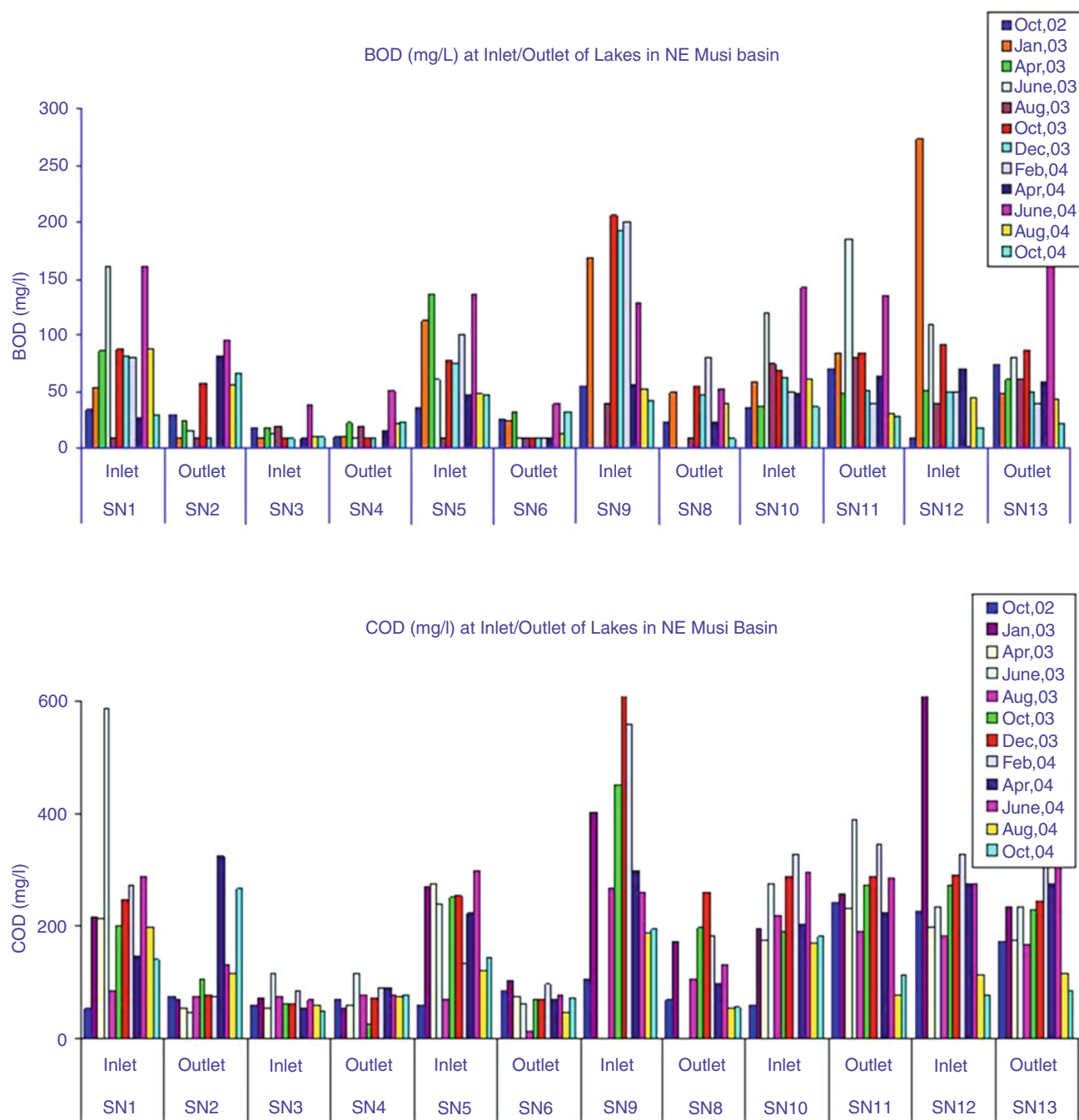
Restoration of Urban Lakes in the NE Musi Basin, Hyderabad, India, Figure 1 Location map of lakes in Northeast Musi basin, Hyderabad.

also has been reported in the earlier studies (APPCB, 2001). The minimum values have been found in Nadimicheruvu due to entry of treated wastewater entering the lake. The average COD concentration in the lakes varies from 140 to 450 mg/L during the study period (Figure 2).

Nutrient load in terms of total nitrogen (TN) and total phosphorous (TP) has been estimated in the lake water as well as from the sediments. The TN concentration in lake water is found varying from 0.2 to 90 mg/L during the study period. The minimum TN values have been reported from Nadimicheruvu <10 mg/L and maximum from Nallacheruvu. The TP concentration in lake water has been varying from 0.2 to 30 mg/L. The minimum value of TP has been reported from Nadimicheruvu and maximum value from Peddacheruvu. The sediments are

also found adsorbing the TN and TP, and their enrichment and depletion depend on the lake water conditions. There is cyclic behavior and enrichment during summer months and depletion during rainy season noticed during the study period. This cyclic behavior, particularly for TP, can be controlled through dredging of lake bed sediments. TN and TP concentrations in sediments are found varying from 0.9 to 136 mg/kg and 4.6–343 mg/kg, depending on the period of observation. Enrichment of TP and TN concentrations in sediments has been noticed during October. Depletion in TN and TP concentrations in lake bed sediments has been reported during the month of February (Gurunadha Rao et al., 2005).

Trophic status index (TSI) is a measure expressing the lake water quality based on nutrient inputs, based on TN and TP values (OECD, 1982). The TSI based on TN



Restoration of Urban Lakes in the NE Musi Basin, Hyderabad, India, Figure 2 BOD and COD (mg/L) in lakes of NE Musi basin during Oct 2002–Oct 2004.

concentrations is varying from 33 to 121. The TSI based on TP concentrations is varying from 81 to 153. The TSI implies that the lakes are mostly phosphate-limited compared to the nitrates. The conditions indicate that lakes are under hypereutrophic condition and demand dredging of lake sediments for phosphate remediation.

Lake water budget

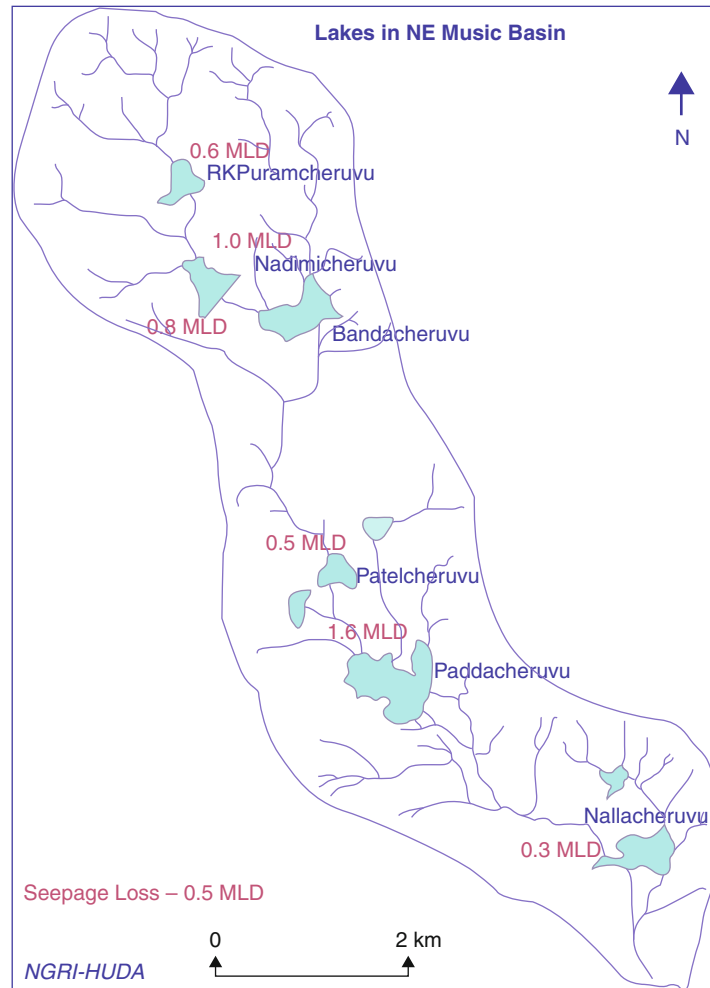
The storage capacity of lakes computed from the bathymetric survey carried out during June 2005 after rising the bunds indicates that Patelcheruvu can hold 115 million liters (ML) at FTL (full tank level). The bathymetric survey carried out during 2003 indicated that Peddacheruvu

could hold 368 ML and Nallacheruvu storage volume being 226 ML at respective FTL. The Patelcheruvu will have a residence time of 1.5 days, Peddacheruvu will have a residence time of 8.8 days, and Nallacheruvu will have a residence time of 8.7 days. Thus, these lake's residence times are found to be <10 days. A groundwater flow model has been constructed, and groundwater balance was computed using zone budget (McDonald and Harbaugh, 1988; Guiger and Franz, 1996). The computed seepage losses and suggested STPs capacity for tertiary treatment at individual lakes in the NE Musi Basin are shown in Figures 3 and 4, respectively.

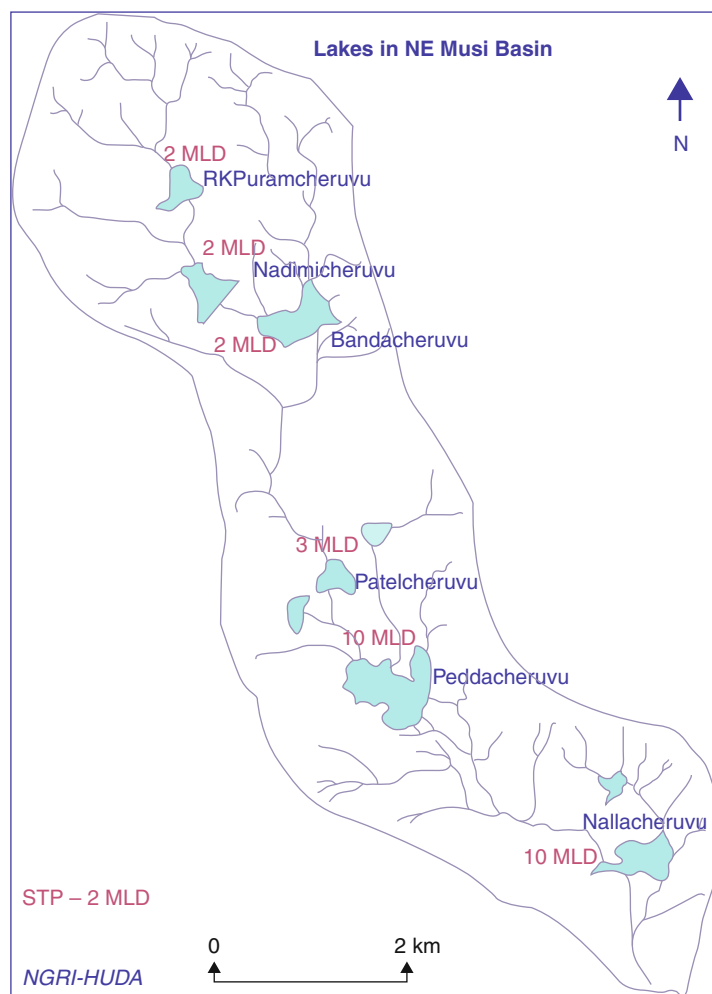
Water budget has been computed with an average actual evaporation loss of 4.5 mm/day from lake water surface at full tank level of Patelcheruvu, Peddacheruvu, and Nallacheruvu are 11 ha, 17 ha, and 17 ha, respectively. A groundwater flow model of the NE Musi Basin computed the zone budget of each lake in the watershed. An STP of 0.6 MLD capacity for tertiary treatment has

been functioning on Nadimicheruvu. The lake surface area is about 10 ha, and evaporation loss at 4.5 mm/day from the lake water surface works out as 0.45 MLD. As the lake is situated in recharge area of the watershed, it contributes about 1 MLD to the groundwater (Gurunadha Rao et al., 2005). Under lake restoration program, it is envisaged to maintain FTL Nadimicheruvu, then it needs a supply of 1.5 MLD of treated wastewater. On a conservative basis with allowance for some outflow from the lake, an STP of 2 MLD capacity is required. It is recommended to enhance capacity of the STP to 2 MLD at Nadimicheruvu based on lake water and groundwater interaction (Figure 3).

Establishment of STPs for tertiary treatment and a wetland for nitrate removal and dredging of lake bed for phosphorous removal seems to be the best management practice implemented under urban lakes restoration program. However, minor modifications in the capacity of STPs are needed in view of lake water interaction with



Restoration of Urban Lakes in the NE Musi Basin, Hyderabad, India, Figure 3 Computed seepage loss from GW flow modeling: Lakes in NE Musi basin.



Restoration of Urban Lakes in the NE Musi Basin, Hyderabad, India, Figure 4 Suggested capacity of STPs at individual lakes in NE Musi basin.

groundwater playing a vital role in lake water budget and in addition to the surrounding urbanization. The surplus inflows to lakes above the STP capacity have to be diverted through separate surface runoff carrying channels bypassing the lakes.

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Cross-references

[Lake Restoration](#)
[Urban Lakes and Ponds](#)

RIVERINE THERMAL BAR

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Synonyms

Convergent frontal zone; Downwelling plume

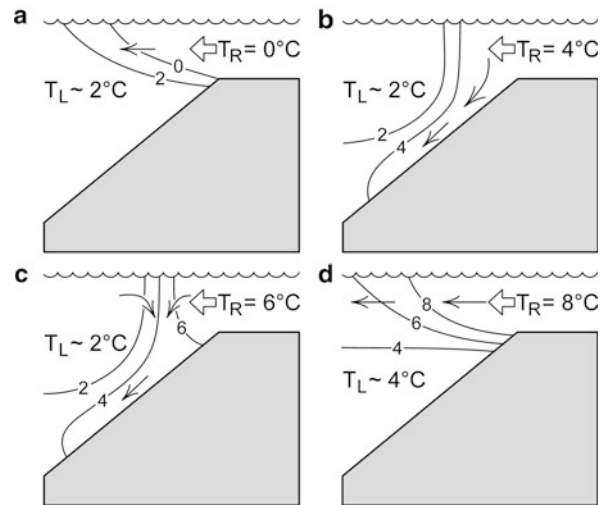
Definition

Riverine thermal bar. A frontal interface and downwelling plume of fresh water at and near the temperature of maximum density (T_{md}) that is formed by the confluence and mixing (cabbelling) of lake and inflowing river waters with temperatures on opposing sides of the T_{md} . The riverine thermal bar (RTB) forms in temperate lakes during spring and autumn overturn and is a special case of the classical thermal bar (TB) that is formed by differential heating/cooling of inshore and offshore waters during spring and autumn transition.

The riverine thermal bar

The thermal bar (TB) is a system-wide convective phenomenon affecting lake overturn in deep temperate lakes that is formed by the confluence of the parent water parcels on opposing sides of the temperature of maximum density ($T_{md} \sim 4^{\circ}\text{C}$). When two such parcels mix, the resulting product is denser than the mean density of the two unmixed components, a process is known as “cabbelling” (see Foster, 1972 for a discussion and etymology). The resulting downwelling plume and overturning circulation cells maintain surface convergence and frontal zone structure. The classical TB (see Tikhomirov, 1963; Rodgers, 1965) forms within a lake with sloping bottom owing to differential heating (in spring) or cooling (in autumn). The riverine thermal bar (RTB) is the special case, whereby an incoming river supplies water on the opposing side of the T_{md} to that of the lake; the resulting juxtaposition and mixing of the lake and inflow results in cabbelling and subsequent sinking of the denser mixtures (Carmack, 1979).

Formation of the RTB rests on the differential warming and cooling of river and lake waters during the spring and autumn transitions. Owing to their shallower depths, incoming river waters will respond more rapidly to spring heating and fall cooling than those of the recipient lake and will thus pass through the surface T_{md} earlier (Carmack et al., 1979). An idealized spring overturn sequence for a riverine temperate lake is shown in Figure 1. In winter, both the lake and the incoming river are colder than $^{\circ}\text{C}$ with the river being somewhat colder and less dense than the lake and so it spreads as a buoyant plume at the lake’s surface (Figure 1a). With the onset of spring, the shallow river warms more rapidly than the lake and, upon reaching 4°C , sinks as gravity current to the lake’s bottom (Figure 1b). Further warming of the river above 4°C creates the antithetical condition,



Riverine Thermal Bar, Figure 1 Schematic of spring overturn in a temperate lake progressing from (a) winter conditions with both the lake and the incoming river are colder than $^{\circ}\text{C}$ and with the river colder than the lake, (b) the onset of spring with river warming to 4°C before the lake, (c) warming of the river above 4°C before the lake so that mixing creates the spring RTB, and (d) both river and lake temperatures above 4°C so that the river plume spreads across the surface.

whereby the river water initially spreads at the lake’s surface but sinks as a downwelling plume as it mixes with ambient lake water, thus creating the spring RTB (Figure 1c). Finally, when the entire lake warms above 4°C , the river plume spreads once again across the surface of the lake (Figure 1d). The same sequence occurs in reverse during autumn as the river cools more rapidly than the lake. Horizontal density gradients are established on both sides of RTB which, under geostrophic balance, force a counterclockwise circulation in the riverward domain and a clockwise circulation in the lakeward domain (cf. Holland and Kay, 2003).

The dynamics of the RTB may also be influenced by the differential compressibility of water, the so-called thermobaric mechanism (Carmack and Weiss, 1991). Because cold water is more compressible than warm water, T_{md} decreases with increasing depth (by about $0.021^{\circ}\text{C} \cdot \text{bar}^{-1}$). In very deep lakes this may affect the dynamics of the descending plume in that the core of the descending plume will continually shift toward its colder side; thus, lakeward during spring overturn and riverward during autumn overturn.

The RTB has important ecological pollutant dispersal consequences (Carmack et al., 1979; Holland et al., 2003). On the seasonal timescale, it is a major transport mechanism driving whole lake convection, ventilation, and nutrient renewal. During periods when the RTB is active, converging flow at the RTB constrain cross-frontal exchange. Thus, the RTB acts as a barrier separating lakeward and riverward domains. In spring, two distinct

phytoplankton grown regimes are found, with higher production rates inshore and maximum biomass accumulation at the convergent front.

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Cross-references

[Thermal Bar](#)

RUSSIAN LAKES

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General information

Russia, with an area over 17 million km², is situated in the arctic, subarctic, temperate, and partially in the subtropical climatic belts of the northern part of Eurasia (Large Atlas of Russia, 2005). Russia has over 2.8 million lakes of various origin, 98% of them are lakes with a surface area less than 1 km². Lakes of Russia belong to the drainage basins of 12 seas and three oceans. An overwhelming majority of lakes in Russia are freshwater lakes, but there occur *brackish, saline, and bitter-saline lakes* in the south of its European territory and in southern Siberia. Freshwater lakes contain a total of 26,500 km³ of water (State Report, 2009). Many large lakes are regulated (Baikal, Onezhskoye, Imandra, Belaye, etc.). Russia partially contains the world's largest lake – the Caspian Sea (surface

area 371,000 km², Kara-Bogaz-Gol Gulf excluded), the deepest lake – Baikal (1,741 m), and the largest lakes of Europe – Ladoga and Onego.

Genesis of lakes

The basins of Russia's largest lakes are mainly of *tectonic* (Baikal, Teletskoye) or *glaciotectionic* genesis (Ladoga and Onego). The group of *glacial* lakes, which are the remains of periglacial reservoirs, comprises such lakes as Il'men, Chudsko-Pskovskoye, as well as *morainic* lakes, of which Seliger is the largest.

Sinkhole lakes in Russia are subdivided into *karst*, *suffosion*, and *thermokarst* ones. *Karst* lakes (small size) occur in areas with dolomitic limestone and gypsum: Onega and Northern Dvina interfluvium, between lakes Onego and Beloe, in the Upper Volga, Ural, Caucasian regions, Tatarstan, and a number of other regions. *Suffosion* lakes are most widespread in the south of West Siberia. The most numerous group is of the *thermokarst* genesis and comprises tens and hundreds of thousands of lakes in the tundra permafrost zone.

The floodplains and estuarine parts of large rivers like Volga, Pechora, Kuban', Amur, Lena, Vilyuj, etc. typically contain *oxbow lakes*. *Volcanic lakes* are located in volcano craters in Kamchatka and Kuril Islands, where one finds also *landslide-dammed lakes*. *Tarns* occur in the Caucasus Mountains. *Liman- and lagoon-type* lakes are plentiful along the coasts of the Sea of Azov, Caspian Sea, as well as the Arctic and Pacific Oceans.

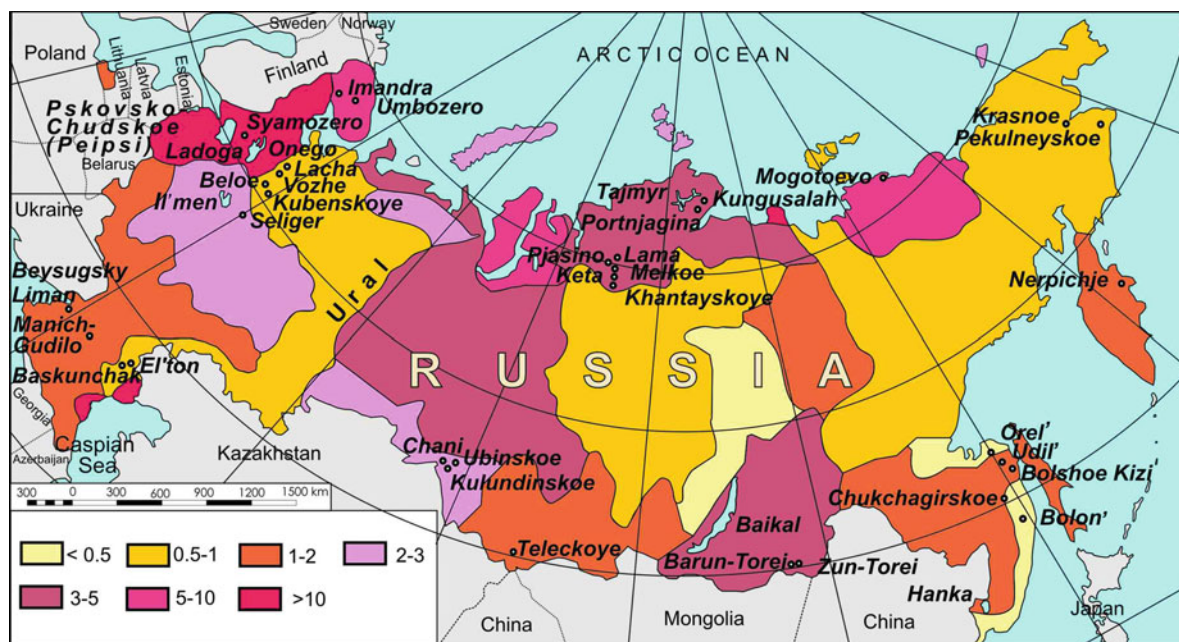
Major lake regions and largest lakes

Let us briefly describe the main lake regions and largest lakes of Russia (Figure 1) relying on the classifications proposed by Sokolov (1952), Domanicky et al. (1971), and in the papers Water Resources (2008) and State Report (2009).

Table 1 shows the principal morphometric characteristics of the country's largest and most economically significant lakes. The largest lake regions are the Northwestern, Caspian, West-Siberian, North-Siberian, Transbaikalian, Amur, and Kamchatka areas.

The Northwestern lake region of Russia covers the territory of the Kola Peninsula, Karelia, Leningrad, Pskov, Novgorod, Tver, and Vologda Oblasts. In addition to small and medium-sized lakes, the Northwestern region comprises the great lakes such as Ladoga and Onego (See *Ladoga Lake and Onego Lake (Lakes Ladozhskoye and Onezhskoye)*), Chudsko-Pskovskoye (shared with Estonia), and many reservoir lakes such as Imandrovskoye (former Lake Imandra), Vygozersko-Onedskoye, Topo-Pyaozerskoye, and others.

Karelia is the richest in lakes which cover a total of about 21% of its area (Filatov and Litvinenko, 2001). Karelia is situated in the eastern part of Fennoscandia. There are more than 61,000 lakes of two major genetic types: tectonic and glacial. The lakes with an area of less than 1 km² predominate. Only 1,389 lakes (about 2% of



Russian Lakes, Figure 1 Lakes and lake regions of Russia.

the total number) are larger than 1 km². The water quality is preconditioned by weak buffering capacity of granites and gneisses, considerable accumulation of humus, low mineralization of the water with low calcium and magnesium concentrations, and often high humus concentrations. About 35% of Karelian lakes have mesohumic waters, 20% of lakes are rich in organic matter. Low-humus waters also account for about 20% of all waters. Hydrogen activity varies from pH 4.07 to 8.34. The lowest pH values (<5.5) occur in highly water-logged areas and in small lakes supplied with atmospheric nutrients. Most of the lakes are oligotrophic (up to 12 mg/l of total phosphorus) or mesotrophic (8–25 mg/l). The lakes are inhabited by almost 700 species and forms of phytoplankton and periphyton, 652 zooplankton, and 138 planktonic protozoan taxa, together with 1,500 species and forms of benthic animals and 54 fish and fish-like animal species.

The Kola Peninsula has about 100,000 lakes contained in tectonic erosion depressions of Fennoscandia. Lakes cover about 10% of the territory. Their waters are fresh or ultra fresh, with a mineral content of 10–30 mg/l and less than 1 mg/l of suspended solids. Many small lakes in the region are acidified because of the low buffering capacity of the catchments and heavy human impact. The largest lake of the Kola Peninsula, *Imandra*, has been converted into a long-term reservoir lake. The natural regime is maintained in Lake Umbozero. For seasonal level variations, there are 1.2 m. The lake freezes over in late October to December and breaks up in late May–June. Lakes of the Kola Peninsula are polluted by wastewaters from numerous industries and by contaminated precipitation. Due to human impact, water transparency in Lakes

Imandra and *Umbozero* dropped from 6–8 m to 3–4 m over 50 years. Most of small lakes are oligotrophic. Waters in the large Lake *Imandra* are meso- and eutrophic; the Kola nuclear power plant operates at the lake (Moiseenko and Gashkina, 2010).

Lake *Il'men* is the fourth biggest lake in European Russia. It belongs to the *Ladoga* Lake drainage basin and features substantial inter-year (up to 7.4 m) and intra-year (187–537 cm) level fluctuations. The lake area varies from 733 to 2,090 km² (Gronskaya, 2008). The ice-covered period lasts from late November to late April. High organic matter content makes the lake water yellowish brown or greenish – during blooms. The lake is the source of potable, industrial, and agricultural water supply – rich in fish. The *Volkhov* River, which originates from the lake, drives the hydropower plant situated 27 km away from the mouth. The plant has no significant effect on the lake level. *Chudsko-Pskovskoye* (*Peipsi-Pihkva* in Estonian) is the European fourth biggest freshwater lake. It is made up of three parts, each having its own name (Noges, 2001). The water is fresh, little mineralized, transparent down to about 2.5 m. The lake freezes over in late November to early December and breaks up in late April to early May. Relative retention time is about 2 years. It supports navigation, commercial and amateur fisheries, and recreation. The shores abound in cultural monuments (churches, monasteries). The main problem for *Chudsko-Pskovskoye* Lake is eutrophication.

Scenic Lake *Seliger*, featuring very complex configuration, lies in the centre of European Russia. It is made up of a number of lake pools connected by short channels. The lake usually freezes over early in November and breaks

Russian Lakes, Table 1 Main characteristics of principal Russian Lakes

		Area, km ²				
Lake	Lake district	Drainage	Lake	Max. depth, m	Water volume km ³	Salinity
<i>European part of Russia</i>						
Ladoga	Northwestern	276,000	17,872	228	908	Fresh
Onego	Northwestern	62,800	9,693	120	292	Fresh
Chudsko-Pskovskoye ^a (Peipsi-Pihkva)	Northwestern	47,800/27,917	3,555/1,990	15.3	25.1	Fresh
Beloye	North	14,000	1,290	20	5.2	Fresh
Il'men	Northwestern	67,200	1,100	4.25	2.85	Fresh
Imandra	Northwestern	12,300	876	67	11.2	Fresh
Vozhe	North	6,260	416	4.5	1.08	Fresh
Kubenskoye	North	14,700	407	13	1.67	Fresh
Manych-Gudilo	Caspian	7,330	344	1.58	~0.17	Salt
Lacha	North	12,600	334	5.3	1.00	Fresh
Umbozero	Northwestern	2,130	313	115	4.65	Fresh
Syamozero	Northwestern	1,580	266	24	1.79	Fresh
Beysugsky liman	Azov Sea	5,190	272	—	—	Salt
Seliger	Central	2,310	212	24	1.22	Fresh
El'ton	Caspian	1,640	152	—	0.2	Bitter-salt
Baskunchak	Caspian	467	106	—	0.01	Bitter-salt
<i>Asian part of Russia (Siberia and Far East)</i>						
Baikal ^b	Transbaikalian	571,000	31,722	1,642	23,615	Fresh
Taimyr ^c	North Siberian	43,920	4,560	26	12.8	Fresh
Khanka ^a	Amur	20,100/18,400	4,190/3,030	10.6	18.5	Fresh
Chany ^c	West Siberian	23,600	1,294	8.5	2.58	Brackish
Khantaiskoye	North Siberian	11,900	822	420	~82	Fresh
Pyasino ^c	North Siberian	24,000	735	10	~2.9	Fresh
Kulundinskoye	West Siberian	24,100	728	4.9	~1.8	Salt
Barun-Torey ^d	Transbaikalian	25,700	578	—	—	Salt
Nerpichye (Kultuchnoye)	Kamchatka	2,550	552	—	—	Fresh
Labaz	North Siberian	1,260	470	—	—	Fresh
Krasnoye	North Siberian	10,100	458	—	~0.6	Fresh
Keta (Khita) ^c	North Siberian	2,990	452	50	—	Fresh
Ubinskoye ^f	West Siberian	2,990	440	2.8	0.88	Fresh
Pekulneyskoye	North Siberian	2,500	435	—	—	Fresh
Portnyagino	North Siberian	1,460	376	—	—	Fresh
Chukchagirskoye	Amur	1,060	366	6	0.73	Fresh
Bolon'	Amur	12,500	338	3.5	~0.3	Fresh
Udyl'	Amur	12,400	330	5	~0.83	Fresh
Magotoyevo	North Siberian	1,170	323	—	—	Fresh
Lama ^e	North Siberian	6,210	318	254	~17,00	Fresh
Orel'	Amur	4,990	314	2.6	~0.80	Fresh
Zun-Torey ^d	Transbaikalian	26,000	302	—	—	Salt
Bolshoye kizi	Amur	5,100	281	4	~0.70	Fresh
Melkoye ^e	North Siberian	12,100	270	22	~1.1	Fresh
Kungasalakh ^e	North Siberian	988	270	—	—	Fresh
Teletskoye	West Siberian	19,500	227	323	41	Fresh

^aWhole lake area (numerator) and area within RF (denominator) are provided for lakes Chudsko-Pskovskoye (with Estonia) and Khanka (with China)

^bwww.lin.irk/intas/morphometry.ru

^cLake Chany, Yudinsky pool excluded

^dArea of Lakes Zun-Torey and Barun-Torey at maximum water levels, multiyear averages

^eAfter Geography of Lake Taymir (1985)

^fAfter Novosibirsk reservoir (1979)

up in mid-April. Its use comprises recreation, passenger traffic, and fisheries.

Several large lakes – Vozhe, Lacha, Kubenskoye, and Beloye – lie in the north of European Russia in Vologda and Archangelsk regions. Lake Vozhe is connected to

Lake Lacha. The multiannual range of the lake water level fluctuations is 1.6 m. Water “blooms” are nearly annual on these lakes. The ice-covered period lasts from mid-November to early May. Lake (reservoir) Kubenskoye is a part of the Volga–Northern Dvina waterway. The lake

freezes over in early November and breaks up in late April. It serves for navigation, fisheries, and recreation. In its natural condition, Lake Beloye had a surface area of 1,290 km² and 5.2 km³ of volume. In 1964, it became a part of Sheksninskoye reservoir. Surface area of the lake at flood-control storage elevation is 1,670 km², full capacity is 6.52 km³. The lake is a part of the Volga–Baltic waterway (Water recourses, 2008). The reservoir freezes over early in November, breaks up late in April, and is used for navigation, power generation, water supply, and recreation.

The Caspian lake region comprises numerous lakes of the Caspian lowland, Volga–Akhtuba floodplain, and Volga delta. This region extends further eastward to north-west Kazakhstan. Playa lakes, which usually form in depressions that are mainly filled with meltwater and river overflows, are widespread there. Average percent cover of lakes in the region is 1–2%, but in the Volga and Terek deltas, it grows to 11% and 12%, respectively (Domanicky et al., 1971). The region has some large, mostly seepage lakes, e.g., Elton and Baskunchak. The climate being arid, the majority of lakes in the region are saline or bitter-saline. Lake Elton – a saline (200–500 PSU), seepage lake – is the biggest saline lake in Europe and one of the world's most mineralized lakes. Water mineralization is 1.5 times that of the Dead Sea. The water contains algae *Dunaliella salina*, which make its color look reddish. The bottom holds salt deposits overlain by mineral hydrosulfuric mud. The lake is comparable with the Dead Sea in its medicinal properties. The Lake Baskunchak salinity is ~300 PSU. The surface salt deposit of the lake is 10–18 m thick. Annual salt mining is 1.5 to 5 million tons, i.e., about 80% of Russia's total.

The Azov–Black Sea region has many liman-type lakes (Domanicky et al., 1971). The biggest *Beysug liman* of the Sea of Azov is used for recreation and fisheries.

Between the Caspian Sea and the Sea of Azov, there lies a large lake Manych-Gudilo (Matishov, 2005), which is now the eastern seepage lake section of the Proletarskoye reservoir. It was impounded in 1932; water mineralization is up to 40 g/l. The lake's fishery value has been lost. A strict nature reserve is located there.

In southern forest-steppe areas of European Russia, the Ural region and the Caucasus lakes are scarce.

Five lake regions are distinguished in the Asian part of Russia (Siberia and Far East). The West-Siberian lake region falls into two subregions: Northern and Southern. The Northern subregion comprises lakes of forest tundra and forest-wetland landscapes of the West-Siberian lowland. The territory contains over 680,000 lakes, only 8,500 of which are bigger than 1 km². The lake cover of the territory is 3.8%. Several lake groups are distinguished in the Southern subregion: Barabinskaya (the biggest lake Chany), Kulundinskaya (including large Lake Kulundinskoye), and Ishimskaya steppe lakes. The percent cover of lakes is high also in the eastern foothills of the Urals (up to 10–14%). In addition to freshwater lakes, there are many saline ones, some are of value for

balneology and fish farming. This subregion features highly mineralized seepage lakes, many of which are saline or bitter-saline. Given the modern surface area of Lake Chany, the lake cover of the territory is 2.3%. Lake Chany is a seepage lake with brackish water. Its area varies substantially due to intensive utilization of river water resources and to climate variations (1,400–2,000 km²) (Fluctuated Lake, 1984). The lake is made up of a number of pools. To preserve the bulk of the lake, the Yudinsky pool was cut off in 1978. The pool is now nearly dry. The lake freezes over in the second half of October to the first half of November and breaks up in May. It is used for fisheries and water traffic. The region contains the large Lake Kulundinskoye, with a channel connecting it to the bitter-saline Lake Kuchuk (181 km² and a max depth of 3.3 m). The lake does not freeze over in winter. The bottom is silted, with a layer of mirabilite (up to 2–2.5 m).

The scenic mountain Lake Teletskoye lies in the south of West Siberia in the immense tectonic basin, surrounded by mountains 2,000–2,500 m high. Its transparency (Secchi depth) is up to 15 m (Physical-Geographical 2008). This lake is the only freshwater reservoir in Siberia with no permanent ice cover. Ice thickness is 30–40 cm, reaching 70–102 cm on harsh winters. Max level fluctuations range is 605 cm. The lake is little mineralized (78 mg/l), ultra-oligotrophic. It is similar to Lake Baikal in origin, catchment and bed geology, climate, and hydrochemical regime. Tourism is developing on the lake and in its catchment.

The periodic drainage freshwater lake Ubinskoye is also located in this region. It is mainly fed by wetlands. In the mid-twentieth century, the lake was famed for plentiful fish.

The North-Siberian lake region is represented by lakes of the West-Siberian tundra zone and North-Siberian, Yana–Indigirka, and Kolyma lowlands – northern slopes of the Putoran mountains. The region has a total of over 600,000 lakes and some 12,600 lakes bigger than 1 km². Lake cover varies from over 10% in River Lena delta and 5–10% in the West-Siberian zone and Rivers Yana–Indigirka lowland to 3–5% in the rest of the region. The region's largest lake is Lake Taymyr. A 1.5-m fall of the water level diminishes the lake surface area to 1,200 km² (Geography, 1985). It is located in the permafrost zone, being a part of a strict nature reserve. The ice cover exists from late September to July, with max ice thickness of 2.5 m. Its flora and fauna consists of the marine aquatic organism complex, as well as species typical of Baikal.

Noteworthy are large lakes Kungasalakh and Portnyagino near the Gulf of Khatanga and lakes Khantaiskoye, Keta, Lama, Melkoye, and Pyasino to the south of it.

Lake Khantaiskoye is the second deepest lake in Russia after Baikal. It lies in a narrow tectonic basin. Lake Pyasino is of glacial origin, with locally waterlogged shores. The lake collects water from large lakes such as Lama, Keta, and Glubokoye. Lake Keta is transparent down to 11 m. Its uses are tourism and amateur fishing.

Lake Lama is connected with Lake Melkoye. Ice thickness is 80–100 cm, shallow, with level fluctuations about 4.7 m. Lakes in the region freeze up early in October and break up in late June to early July.

The Circumpolar Maritime lake region (Domanicky et al., 1971) comprises the lake-rich tundra zone of the Arctic Ocean coast. The lakes are predominantly of thermokarst genesis. The largest saline lake Mogotoevo is connected to the East Siberian Sea via a channel.

The Transbaikalian lake region comprises 50,000 diverse lakes, including Russia's largest freshwater lake – Baikal. Other reservoirs to be mentioned are Eravinskiye and Arakhleyskiye groups (mainly freshwater drainage lakes) and Lakes Zun-Torey and Barun-Torey, which may dry out in low-water periods. The region's lake cover, including Lake Baikal area, is 3.9%. Zun-Torey is a saline seepage lake reaching 300 km² on high-water years and nearly vanishing on dry years. When full, it becomes connected to Lake Barun-Torey – seepage, saline, intermittent lake partially located within the Daurisky nature reserve. It is frozen from November to April, down to the bottom in winter. A small part of the large lake Ubsu-Nur (total area 3,350 km²) is situated in Russia, on the border with Mongolia. Ice covered from October to May, it has high salt content (up to 18 g/l), with sulfate and sodium ions.

The Amur lake region comprises lakes of the River Amur drainage basin, downstream of the Shilka and Argun' river confluence. The biggest lake is Khanka. The region also harbors many fairly big lakes more than 250 km² in area, including those connected via channels to Amur, and fed by the river during floods. The region's lake cover, including Lake Khanka (shared with China), is 1.1%. Lake Khanka is the largest freshwater lake in the Far East of Russia, shared by Russia and China. Its water is moderately polluted, and metal ion content is high. The lake harbors many fish and aquatic invertebrate species, including many endemics (State Report, 2009). Lakes Bolon, Udy, Orel, and Kizi are connected to the Amur River via channels, and their water quality during floods depends on the Amur water quality. They are ultra-freshwater lakes with 35–149 mg/l mineral content, pH 5.8–8.8, and high nutrient concentrations. Lake Chukchagirskoye features high content of suspended solids, which settle down in winter. Its organic matter content is high, with mineralization of 30–80 mg/l. It is ice covered from late October to early November to May.

The Kamchatka lake region contains more than 40,000 lakes, of which 199 are larger than 1 km². Lakes of the region are quite diverse (Sokolov, 1952) including the so-called volcanic lakes – the largest ones being Kurilskoye and Kronotskoye – as well as lagoon-type lakes such as Nerpichye, in Kamchatka River mouth. Percent cover of lakes is 1.1%.

There are volcanic lakes (*caldera type*), e.g., Lake Kurilskoye holds the largest cockeye salmon stocks in Asia. The water volume is 14.6 km³, area is 79.25 km², and max depth is 316 m (Ponomarev et al., 1986). A river

connects it to the Sea of Okhotsk. Level fluctuations' range is 1.3 m. Mineralization is 69 mg/l. The lake is a nature reserve and a nature monument.

The Kamchatka's largest lake Nerpichye is of *lagoon type*, connected to the Kamchatka Bay, Pacific Ocean. The lake abounds in fish, a special land-locked form of herring lives there. Lake Kronotskoye is the largest freshwater lake on Kamchatka, located within the Kronotsky nature reserve, 30 km north of the world-famed geyser valley. It is of volcanic origin, formed when volcanic lava dammed a river valley. The level fluctuations' range is several tens of centimeters. It is ice covered from late December to mid-May.

Islands in the Pacific and Arctic Oceans contain about 40,000 lakes with a total area of 3,517 km² (Domanicky et al., 1971).

Russia contains lakes listed as UNESCO World Natural Heritage – Baikal and Teletskoye – as well as drainage basin of Lake Ubsu-Nur, and Lake Kurilskoye is a nature reserve and a nature monument within the “Volcanoes of Kamchatka.” Besides, Lake Chany and its catchment are in the UNESCO list of wetlands of international importance.

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Cross-references

Baikal, Lake
 Caspian Sea
 Ladoga Lake and Onego Lake (Lakes Ladozhskoye and Onezhskoye)
 Russian Lakes, Geographical Classification
 Russian Water Reservoirs

RUSSIAN LAKES, GEOGRAPHICAL CLASSIFICATION

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Lakes of the East European Plain (Russian part)

The East European Plain is one of the largest plains in the world, with an area greater than four million square kilometers (Figure 1). Most of it is part of the Russian Federation. Nearly all of the Russian portion settles along the Precambrian plate. The latitudinal-zone landscape differentiation from tundra up to steppe is pronounced. The landscapes change from weak to typically continental by longitude.

During the last million years, the so-called Quaternary Period, the East European Plain was covered by continental glaciers no less than four times. The most ancient glaciations, "Okskoe," occurred about 500,000–600,000 years ago and reached the River Oka basin above the confluence of the Oka and the Volga. Later, about 200,000 years ago, the maximal glaciation "Dneprovskoe" followed. At this time the heavy ice sheet was distributed to the south of Kiev, Kharkiv, and Voronezh; its two glacier tongues reached the south along the valleys of the Rivers Dnepr and Don. The subsequent "Moscow" glaciation took place about 150,000 years ago and reached the latitude of Moscow. And more recently in geological chronology, about 80,000–12,000 years ago, the glacier that reached only up to Valdai covered the northern part of the Russian Plain; consequently, this glaciation is named "Valdaiskoe." The Valdaiskiy ice sheet covered Scandinavia, Finland, a hollow of Baltic Sea, and adjoining areas of Northern Europe with a heavy cover. Its thickness in the center, in the Scandinavian mountains, reached 2,500 m, and on the borders about 500–700 m. The result of this glacial activity in the northern part of the East European Plain is the prevalence of glacial and water-glacial forms of relief.

The East European Plain can be divided into three parts by the peculiarities of lake hollow formation: Karelia, the

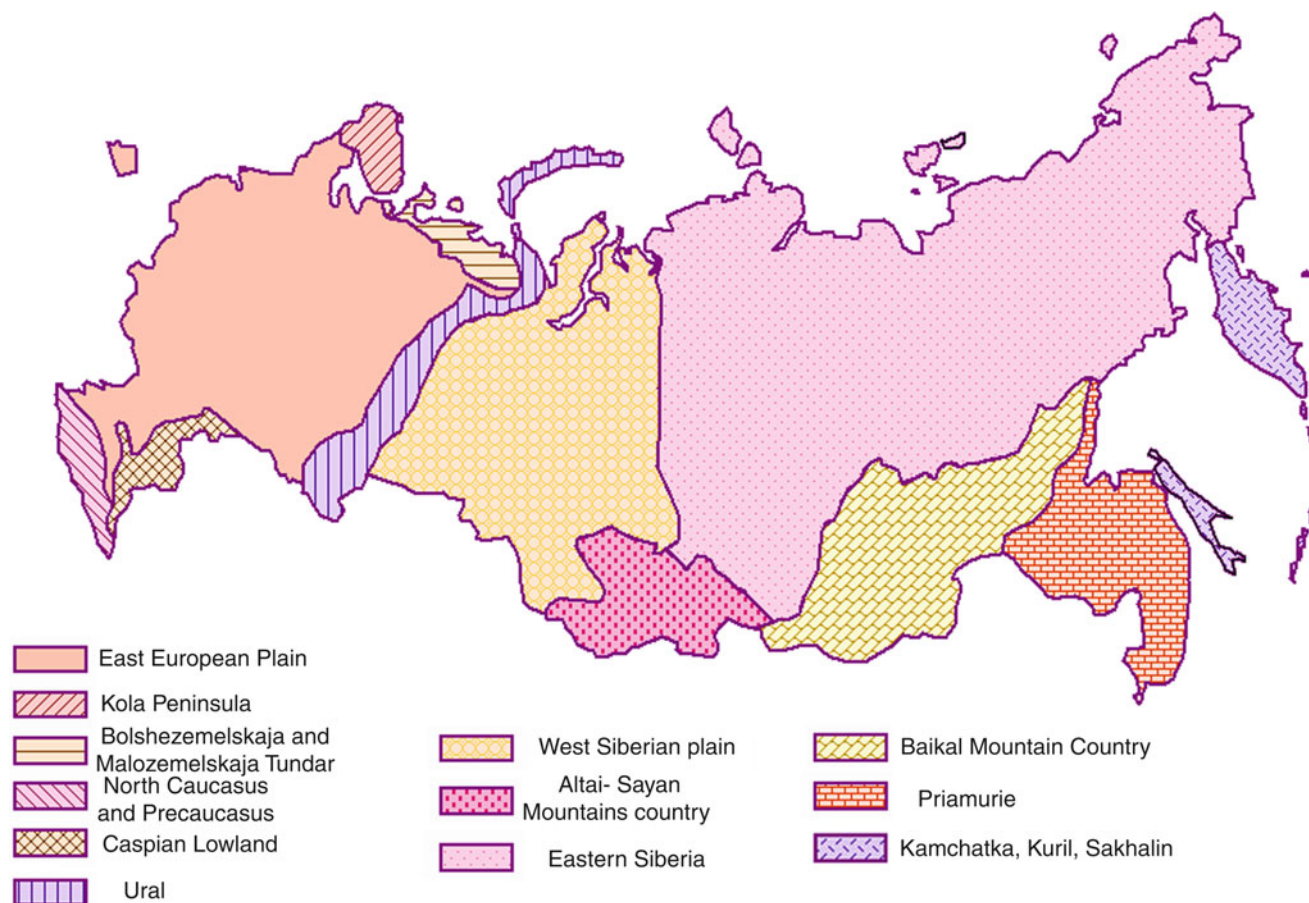
northwest of East European Plain, and the center and the south of East European Plain.

At Karelia there are many lakes (they cover about 11% of the territory). It underwent active plowing during the advance of the last glaciation. Over thousands of years, the heavy ice sheet, reaching a height of more than 1,500 m, was situated there. At the time of glacier contraction, violent streams of thawed snow flowed through the hollows formed at its bed. As a result, the formation of lake hollows of a glacial-tectonic or glacial origin took place here. Today in Karelia there are about 60,000 lakes, including the largest lakes in Europe – Ladoga and Onego. Moreover, Lakes Vygozero, Topozero, Segozero, Pjaozero, Vodlozero, Kuito, Sjamozero, Paljezero, and Tikshozero are of considerable size. The total area of all the lakes of Karelia makes up nearly 40,000 km². At the same time, more than 97% of the lakes have a water surface less than 1 km², and their general total area makes up about 10,000 km². Many lakes (about 75%) are located in the northern part of Karelia, between 63 and 66°30'N. The lakes of Karelia belong to the White and Baltic Sea basins. All large and middle and the majority of small lakes have the outflow; this is favorable to the breeding of fish and other organisms. Connected by rivers, the lakes form a complex system with naturally regulated drainage. Annual fluctuations in the levels of the majority of the lakes average about 0.5 m.

The lakes frequently consist of one narrow, long stretch and many narrow lips and gulfs. Theirs characteristic feature is numerous islands. A relief of the bottom is extremely irregular; areas of great depth are frequently stretched as the narrow trenches alternate with underwater rises or banks. Quite often, coastal heights ("selgi") approaching the lake continue under water. Depths change from 10 up to 100 m and more, however, maximal depth on average equals 20 m. The significant depths are favorable for the distribution of kryophila fishes: grayling, trout, and whitefish.

In deep Karelian lakes the temperature of the water in benthonic layers in the summer reaches about 7–10°C, at the depth of 10–15 m the temperature increase from 12°C up to 17°C, and the surface layers warm up to 19–23°C. These are typical lakes of a temperate zone, with the return temperature stratification during the winter period and direct stratification in the warm part of the year. The ice regime, regardless of meteorological factors, depends on the area of water surface, depth, and volume of lakes. With the approach of winter the small lakes and gulfs of the big lakes become covered with ice, and the coastal parts of the big lakes follow. Finally, the central parts of the big reservoirs freeze. The majority of lakes freeze from the end of autumn or beginning of winter until April or May.

Practically all Karelian lakes are fresh, with very weak mineralization of waters (10–20 mg/l) and low conductivity (5–8 µS). Slightly greater mineralization is characteristic of Zaonezhie (from 30 mg/l). In the lakes the hydrocarbonates usually dominate among the ions, and



Russian Lakes, Geographical Classification, Figure 1 Physico-geographical regionalization of Russia (According to Isachenko and Shlyapnikov 1979).

seasonal variability of mineralization structure is small. Oxygen conditions are favorable for the majority of lakes. pH ranges from 6 to 8; only in acidic lakes is it lower: 5–6. The organic substance is generally indigenous and rich in nitrogen. Intensity of the development of primary production and biomass usually is not high.

Oligotrophic lakes are typical for Karelia. The majority of them are situated in the north of Karelia, in northern Priladozhie (Varpajarvi, Salmentakaynen); slightly fewer at the Onego-Ladoga watershed (Lizhmenskoe, Topornoe, Suvyajarvi) and Shuisko-Sunskiy watershed. Many small Karelian lakes belong to a class of mesotrophic lakes; most are situated in northern Priladozhie (Lakes Pjuhjarvi, Kotjarvi, Yaimajarvi), at the Shuisko-Sunskiy watershed (Sjapchezzero, Mjaranduksa) and Onego-Ladoga watershed (Njalmozzero, Nikonovo). Eutrophic lakes are rare; they are found at the Onego-Ladoga watershed (Hlebnoe, Pelteri, Kaskozero) and Shuisko-Sunskiy watershed (Vuozhozzero, Vohtozero, Naidemozero, Peldo). Often their location is connected to a cultural landscape, but for some lakes the trophic level is caused by very shallow depths or by other reasons of natural character. In Karelia

there are many acidic (acidotrophic) lakes, found at the Onego-Ladoga watershed and also in the Veshkelitskaja group of lakes and near Konchezzero. They are short-drainage lakes with surface areas from 2 up to 100 ha, but in some lakes it is greater. The average depths change from 2 up to 9 m, maximal is from 4 up to 24 m. The characteristic feature of acidic lakes is an acid reaction of water (pH less than 6) in combination with the small values of permanganate oxidizability (usually below 6 mg O/l). At the Onego-Ladoga watershed there are dystrophic lakes, too, the largest of them having surface areas not exceeding 50 ha.

The northwest of the East European Plain includes most of the northwestern region and the northern region of Russia. The southern border passes through the Valdai Hills and coincides with the southern border of distribution of the last glaciation. In this part of the East European Plain there are many lakes also, but not more than in Karelia (they cover from 1% to 3% of the territory). Most lake hollows are formed in the depressions of moraine relief that remained after the glacier contraction. The height of the moraine here reaches from 60 to 80 up

to several hundred meters (Luzhskaja, Sudomskaja, Bezhanitskaja Heights, etc.). The formation of lakes is connected with thawing of buried ice blocks or with destruction of enormous ice fields. Some lakes occupy the bottoms of former river valleys filled with fissured ice or the narrows formed by thawed glacial waters. Such lakes are usually strongly elongated. They are shallow with average depths up to 3 m, maximally 6–8 m (Lakes Jazno, Dolysskoe, Rudo). Extensive glacial lakes were formed on the flat plains near the edge of a glacier. In the process of glacier contraction they were drained, and the flat lake plains were formed in their place. Today there are many lakes here. Lakes Pskovsko-Chudskoe, Ilmen, Beloe (White), Kubenskoe, Vozhe, Lache, Kenozero, Kozhozero, Undozero, and Lekshmozero are the largest postglacial lakes, with areas surpassing 100 km². Average-size lakes include Zhizhitskoe, Dvin-Veliskoe, Polisto, Sebezhscoe, Nevelskoe, Necheritsa, the Bolshoy Ivan, Ale (Pskovskaja oblast), Vyshtynetskoe (Kaliningradskaja oblast), Kolgachihinskoe, Chelozero, Pelozero, Sharozero, Syvtzero, Kovozero, Krasnyi Okun (Red Perch), Sojalskoe and B. Pinezhskoe (Arkhangelskaja oblast), Samro, Vrevo, Cheremenetskoe, Vjalie, Stregno, and Sjaberskoe (Leningradskaja oblast).

The floodplain lakes located along the majority of the large rivers also have a wide distribution in this region. Interesting examples are the Kuilokskie salty lakes, which are located not far from the River Pinega and are used for salt extraction. Their origin was connected to chemical and mechanical destruction of saliferous breeds located there. In places where soluble rocks, such as limestones and dolomite, lie close to a surface, the karstic lakes are distributed. They are situated at Belomorsko-Kuloiskoe Plateau, at Onego-Dvina watershed, and also in the area of Megorskaja Ridge (east of Leningradskaja oblast). Karstic lakes periodically disappear. Lake Koigushskoe (Megorskaja Ridge) is a typical example of these lakes. Some karstic lakes are intensively overgrown and become bogs. On the coast of Finland Bay there are some lagoon lakes with salty water (for example, Lake Gorvaldajskoe formed due to a branch from Finland Bay by a narrow strip of sandy dunes).

In total, in the northwest there are about 30,000 lakes of glacial (moraine), and, also, river and karst origin. The majority of lakes belong to the Baltic and White Sea basins, and to the lakes of Upper Volga (basin of the Caspian Sea).

The number of oligotrophic lakes at the north and northwest of the East European Plain is a small. They are confined mainly to the north (Arkhangelskaja oblast) of this territory. Mesatrophic and eutrophic lakes prevail. The majority of lakes are in “a stage of ageing” – the hollows of many deep-water lakes are characterized by significant accumulation of mineral and organic deposits overlapping the fine roughnesses of the bottom. Their coasts are flatter, the depths accrue gradually, and the shoals are typical. The zones of emerged (aero-aquatic), floating, and submerged macrophytes are strongly

pronounced near the coast. The active development of phytoplankton is observed. The transparency of water is low, up to several meters. The largest lakes of this type are Pskovsko-Chudskoe, Ilmen, Zhizhitskoe, Sebezhscoe, and Bolshoy Ivan.

The hydrological regime of the lakes is characterized by small changes in water level. Significant changes in level are observed in the majority of karstic lakes. The striking exception is Lake Ilmen, the level of which can change by 7 m. The temperature regime of lakes is substantially determined by the depth of a reservoir and its susceptibility to wind activity. The majority of deep lakes are characterized by the formation of direct stratification during the summer, return stratification during winter, and two periods of homothermy (spring and autumn). However, the formation of clear thermocline and significant divergences between superficial and bottom temperatures are observed only in the few deepest lakes. The water in shoals usually mixes up almost completely. The summer surface temperature is usually 18–20°C, and for shallow lakes is 24–26°C. The formation of an ice cover on the majority of lakes occurs in November–December, and an ice break in March–May (depending on latitude and lake size). On some reservoirs the ice-field is not formed annually (the lakes of Vishtvenetskaja Height). The mineralization of water is usually not high, up to 100–150 mg/l, and conductivity is 6–30 µS. Excessive mineralization (to 400 mg/l) is observed in lakes of Bezhanitskaja Height and in some lakes of the Arkhangelskaja oblast. The accumulation at the bottom of a large mass of sapropel is typical for many lakes of the northwestern part of the East European Plain. Sapropel is extremely valuable and is widely used in the economy.

The center and south of the East European Plain includes the Central and Central–Chernozem regions of Russia and the Middle Volga region. In this territory there are the fewest number of lakes that have been subjected to the last glaciation. However, the previous glaciations (Moscow, Dneprovskoe) left a trace in the formation of its relief and took part in creation of some lake hollows. In the center and the south of the East European Plain there are some 1,000 lakes. Most are small in size; only a few surpass an area of 10 km²: Lakes Plestcheevo and Nero (Yaroslavskaja Oblast), Galichskoe and Chuhlomskoe (Kostromskaja Oblast), Asylkool and Kandrykool (Bashkortostan), Velikoe and Svjatoe (Mestchera), and a few others. These lakes belong to the basins of Black and Caspian Sea.

The floodplain and karstic lakes prevail in this region. Lakes Plestcheevo, Nero, Gavrilovskoe, Sapsho, Chistik, Baklan (Cormorant), and Rytoe are the rare examples of glacial lakes. Among floodplain lakes there are many meander (oxbow) lakes; their form is lengthened or horseshoe-shaped, preserving the bends of a river channel. Such lakes are widely distributed in the Volga region and in the flood plain of the Rivers Kama, Oka, and Desna. Karstic lakes are typical in most of the center

and south of the East European Plain; many of them are situated in the Volgo-Vjatskiy region, Bashkiria, and Penzinskaya Oblast. Karstic lakes have significant depth and an oval form. Often they are closed water bodies without a superficial drain and even inflow, and their surface area is insignificant. Many lakes are extraordinarily clean and highly transparent. Their mineralization varies and is usually determined by the character of the underground water connected to lake. Water of deep karstic lakes usually is low in temperature, remaining cold even in the summer. Another feature is their low ability to freeze. The largest karstic lakes are Asykkool and Kendrykool (Bashkortostan), with surface areas of 23.5 and 15.6 km², respectively.

The hydrological regime is determined by the origin of the lakes. Many lakes have rain, snow, and underground feeds. Karstic lakes are mostly characterized by the presence of underground feed. The feed predetermines the mineralization of lakes. On average it is about 100–200 mg/l and the conductivity is 18–60 µS; in karstic lakes the mineralization may be greater, from 1 g/l up to 12 g/l.

Lakes of the Kola Peninsula

The Kola Peninsula is in the far northwest of the European part of Russia in the northeast outlying districts of the Baltic Shield. The peninsula geological formation consists mainly of Precambrian and Paleozoic crystalline rocks and its relief and low evaporation are favorable for many lakes. And indeed there are some 110,000 lakes in the Kola Peninsula. The largest lakes have a glacial-tectonic origin and, during the Quaternary glacial period, lake basins were substantially reformed and sculpted by glacial erosive activity. Most of the lakes are characterized by low water temperatures, long periods of ice cover, cleanliness, high transparency conditions up to 11 m, low mineralization, and low organic substances. Almost all lakes are oligotrophic.

The largest lake is Imandra, with a surface area of 812 km², maximum depth 67 m, and a 127 m elevation. Many rivers enter the lake, including the Pirenga and Moncha, forming a complex river-lake system. The largest outflow river is the Niva. There are more than 140 islands, the largest being Erm Island of 26 km² in area. The lake feed is mainly by snow and rain water; lake cover is observed from December until May. There is an abundance of fish, including whitefish, grayling, and loach. The deepest lake in the Kola Peninsula is Lake Umbozero, with a maximum depth of 115 m. Other large lakes include Lovozero, Notozero, Kovdozero, Kolvockoe, Kanozero, Vyalozero, Segozero, Ondomozero, Enozero, Babozero, Lyavozero and Kolozero.

Practically all small lakes in the Kola Peninsula have had little limnological investigation and only a few in the stony tundra on the coast of the Barents Sea, such as Lakes Zeleneckoe, Akulkino, and Pozdnyakovskoe, have been ecologically investigated. The ice cover extends for at least 8 months. The oxygen content in the water is high,

with a pH of 6.5–7, and transparency is also high at 4–5 m. A homothermal period after ice break is usually not maintained for a long time, however, the difference in temperature between the surface and bottom layers does not exceed 4°. The lake water has low mineralization, the dominant ions being Cl[−] and HCO₃².

The amount of organic substances is small and substantially stable, and there is an insignificant amount of iron or biogenic elements. The *fauna* dominating in cold waters is of palearctic and holartic forms, and there are the glacial *relicts*.

The following lakes have been investigated in forest tundra and the north *tayga* zone: Lakes Konentyarv-Kolgiyarv, Polyarnoe, Berezovoe, Vyalozero, Senozero, Pasmozero, and Velikom. In many of these lakes banks are formed by boulders, shingle, and gravel as well as sandy deposits. Bottom sediments have low content of organic substance and a prevailing component of their structure is authigenic silica diatom in the phytoplankton. The intensity of photosynthesis is low and absorption of oxygen intensive, resulting in a negative daily balance of organic substance. In the lakes of the forest tundra, mineralization is low and the water is of chloride–sodium type. Lakes are subject to strong winds and oxygen saturation is high. The structure of phytoplankton is varied, about half belonging to a type Chlorophyta.

Biomass is not more than 0.2 g/m³ and photosynthesis is 0.3 mg O/l day

In lakes having higher organic substance in bottom sediments, the *zoobenthos* is richer and *Chironomidae* is the dominant family.

The ecological status of the lakes of the Kola Peninsula is good, although problems with dumping of large quantities of waste, some polluted, has been experienced, mainly from industries and the cities of Monchegorsk, Zapolyarnyi, Nickel, and Murmansk.

Lakes of Bolshezemelskaja and Malozemelskaja Tundra

The North-Pechora tundra province is situated at the northern part of the Pechora Lowland, to the north of the Polar Circle. This territory is a wavy plain with numerous heights and ridges. The Malozemelskaja tundra is situated between the Rivers Timan and Pechora. It is a monotonous, marshy, and lacustrine lowland with separate frontal moraine ridges. The Bolshezemelskaja tundra is situated to the east of the River Pechora; it is an extensive lowland occupied with bogs and lakes.

The surface of tundra abounds in numerous small lakes whose origin was in thermokarst processes. Thermokarst lakes are subject to periodic disappearance and to reoccurrence. There are also lagoon lakes, generally small in size, with lengths under 2 km and depths about 3–4 m. The lakes are located among bogs and have peat or swale coasts. Larger lakes are found in areas of glacial sediments. Among the largest lakes are Golodnaja Guba (Hungry Lip), Pilnja, Vashutkiny, Vatiarty, Urdjuzhskoe, Bolshoe, Tainto, and Oshkaty.

The lakes of Bolshezemelskaja and Malozemelskaja Tundra are situated in a cold continental climate. These are oligotrophic lakes with ice cover for most of the year and low water temperatures in summer. Bathymetric surveys and water quality investigations have been carried out on the Prosunduiskie lakes, the lakes of Harbeiskaja System, and the Pilnenskaja group of lakes. The largest lake of the Pilnenskaja group is Pilnja, with a surface area of 51.6 km², average depth 1.4 m, and volume 0 km³. The transparency is only 1 m. Green and diatom algae are the predominant forms of phytoplankton. Fish life includes whitefish, grayling, northern nine-spine smelt, and several types of salmon.

In Nenets in the east of the Bolshezemelskaja Tundra, the Harbeiskaja system includes three connected lakes: Golovka, Bolshoi, and Maly Harbey, which are surrounded by shallow lakes. The system includes the River Sayda of the River Usa system. The catchment is marshy. The lake coastlines are varied, with many bays, and there are numerous islands. All lakes are free from ice cover during the short period of from July to September. Lakes are homothermal as a result of wind mixing. The lake water has a low mineralization and contains biogenic elements of phosphorous and ammonia, but nitrites and nitrates are almost absent. Organic substances in the lake water have an allochthonous origin. The photoplankton complex includes widespread boreal and subalpine species. Ichthyofauna is of the arctic freshwater kind.

The Prosunduiskaja lake system has 29 lakes with a total area of 26.4 km². Most lake basins show evidence of relief and low banks. The duration of the frost-free periods averages 70–80 days and the lakes are opened in the middle of June. The Prosunduiskie lakes belong to a class of small water bodies of area from 10 to 535 ha. The greatest depth does not exceed 13 m. Bottom sediments are mainly of a sandy nature and most lakes have a sandbank form of shoreline of about 1.5–2.0 m. The stratification is observed in summer on deep-water sites of lakes. During the open water period the content of dissolved oxygen is high and nearly fully saturated, mainly as a result of intensive wind mixing. The lake water is poor in biogenic elements and investigation shows that there is carbonic acid present. Ichthyofauna is represented by white salmon, whitefish, ide, and migrating forms. Some species continue to live in the lakes.

Lakes of the North Caucasus and Pre-Caucasus

The Caucasus Mountain country belongs to the Alpine folded zone. There is a considerable variety of landscape, from pluvial variations of deciduous and Mediterranean types to sub-boreal Steppe, semi-desert, and subtropical desert with belts of herbaceous Alpine glaciers. In the North Caucasus there are more than 1,000 lakes, most of them being confined to middle and high altitudes. The lakes are of glacial, collapse, or karstic origin, although lakes are also found in the foothills.

The largest lake of the foothills of Krasnodar Kray is Lake Abrau. The lake is fresh water, 2.5 km in length, maximum width is 600 m, and surface area is 1.6 km². It is believed that the lake was formed as a result of karstic collapse or that it is a remainder of an ancient Cimmerian freshwater basin. There is also a version that connects its origin with an enormous landslide. Another large foothills lake is Lake Samurskoe, with a surface area of 0.46 km².

Estuaries and lagoons are widespread along the Black Sea and Azov coasts, and are also found between the mouths of the Don and Kuban Rivers. There are about 250 water bodies here, including both fresh and saline lakes of the Kuban River Delta. The largest of these is the Eiskiy estuary, whose surface area is 244 km², although there is also the large group of Beysugskies and Abtarskies estuaries with considerable area. Among the Kuban Delta lakes, the large freshwater lakes include Ahtanisovskiy (336 km²), Vityazevskiy (55 km²), and Kyzyltashskiy (142 km²). All of them are shallow.

The picturesque lakes of the middle and high altitude of the Caucasus have lead to worldwide interest in the area. However, the difficulty of access has had an adverse effect on their investigation. The lakes have high transparency and are noted for the blue or sea-green color of their waters. They are divisible by their origin to damming and landslide lakes, glacial and moraine, and karstic and tectonic.

Natural damming of lakes was a result of collapse and landslides damming up the valleys of mountain rivers with natural barriers and weirs. Landslide lakes are found in the catchments of Chanty-Argunskiy and Shero-Argunskiy watersheds and in the Shikoroy. A typical lake is the high altitude Lake Kezenoiam situated at an elevation of 1,860 m at Andiyskiy Range near the border of the Chechen Republic and Dagestan. The lake was formed by a landslip that dammed the valleys of the River Horsuma and the River Kauha. The lake has steep slopes and a flat bed. The natural dam is 100 m high. The surface area of the lake is 2 km and depth 72 m.

Another lake of the dammed type is Lake Mochoh (Dagestan) situated at an elevation of 1,600 m at the River Mochohtau Andiyskiy basin. The lake was formed by the Mochohskiy landslide in 1963. Its length is 1.3 km, width is 300–400 m, and the depth ranges from 20 to 30 m with a maximum of 60 m.

The following lakes were formed by landslides, avalanches, or earthquakes: Lake Achipsta (surface area 60,000 ha), situated in the Caucasus Biosphere Reserve, formed as the result of a huge avalanche over the Achipsta River. Lake Inpsy (surface area 7.5 ha) formed during an earthquake as a result of a landslip that dammed up the River Tzahvoa and others. The following are examples of tectonic lakes: Lake Hyrtana situated on the Main Caucasus Range near the border of Dagestan and Azerbaijan. The lake is situated at an elevation of 3,210 m and is the highest lake in the North Caucasus. Lake Galanchozhskoe, situated at an elevation of

1,533 m in the River Osu-hi valley, length 450 m, width 380 m, and depth at the center 31 m. There are many widespread deep karst lakes in North Caucasus, the best known of which are Lake Cerikkel at Kabardino-Balkaria, with a depth of 368 m, and Lakes Pahurov and Sherek-Yana, with depths of over 200 m.

Mountain lakes of North Caucasus are overflow and closed basin. Depending on groundwater flow, lakes vary in salt content, although most have a good supply of fresh water. Depths are considerable, especially in karstic and tectonic lakes. High altitude lakes have low temperatures even in summer and suffer a long freezing period. For example, Lake Kardyvach (upper course of the Mzymta River) is closed by ice almost all year. Ice floes are present even in summer. Almost all lakes are oligotrophic and poor in organic content. They are fed by snow, rain, and groundwater in many cases. If feeding is deficient some lakes become shallow in summer (for example, Lake Achipsta).

Many lakes in North Caucasus have a short life; some disappear, especially during the washout of dams. For example, Lake Dultychayskoe emerged in 1905 and vanished in 1958. Other lakes slowly drain away into rocks and dry up or flow into swamps.

At the same time, however, tectonic and mudflow activity set up the formation of new lakes. The principal features of the mountain lakes of the Caucasus are their aesthetic value and their preservation of a pristine environment due to their remoteness.

Lakes of the Caspian Lowland

The Caspian Lowland is part of the Turanskaya Plain – the lower lands with accumulative and arid-denudation relief on the epihercynian platform. The northwest part of the Caspian Lowland belongs to Russia. The climate is arid. The lakes, about a thousand of them, are generally saucer-shaped depressions. The origin of lakes is tectonic or damming. Depending on their location some lakes are somewhat saline with various concentrations of salinity. Many of the lakes are temporal, with water infill during spring snowmelt only, they contain fresh (melting) water. Stretching south of Volgograd over the Kalmykia Steppe there are the Sarpinskies lakes including Lakes Sarpa, Teatca, Barmantcak, Prishib, Hanata, Kanurka, Deed Hulsun, Buzga, and others. These shallow lakes dry up in summer and, because of the ingress of sewage, their quality is generally low.

Within the Volga-Ahtubinskaya flood lands and the At Volga Delta there are the “ilmens” or the “poloy.” These lakes are concentrated in the west of the Volga Delta and their origin is connected with wind activity and the contraction of the Caspian Sea. The contraction of the Caspian Sea has had the effect that the water in the lakes has filled the deeper parts only. The lengths of these lakes vary from hundreds of meters to some kilometers and widths within the range 150–1,000 m and depths from 0.5–3.5 m, the largest being Lake Bolshoi Beshkull, 10 km in length. At the edge of the Volga Delta the “kultuks” lakes owe their

origin to their separation from the sea by sandy sediments, spits, or banks. The Kultuks are shallow (0.5–1 m) and with warm summer water they are covered by white water lilies, water chestnuts, and reeds.

Some lakes maintain water all year and are substantially fresh, but the majority of lakes are salty. Salt extraction of saline lakes continued to the twentieth century. The well-known Malinovoe (Crimson) Lake of Empress Ekaterina was noted for its elegant rose-crimson color due to the microorganisms (*Seracia sallinaria*). The best known salt lakes are Lakes Baskunchak and Elton. Lake Baskunchak has a surface area of 106 km² and elevation 21.3 m. It is a tectonic lake compensated by salt strata formation. The depth of salt surface deposits is up to 4 m and as much as 18 m near the coast. Surface brine, up to 0.8 m in depth, appears in winter and spring. The spring feed to the lake amounts to 24 million liters and 2.5 thousand tons of salt per day. Accumulation of salt amounts to up to 50 m and deposits of salt up to 10 km in the earth's interior were discovered under the lake. Lake Baskunchak is part of the Bogdansk-Baskunchakskiy Nature Complex, declared as a natural reserve in order to preserve the original flora and fauna.

Lakes of the Ural

The Ural-Novozemelskaya Mountain Country is a Hercinian folded construction that has been the subject of thousands of years of denudation and of more recent creation of low and average mountains in a meridional direction from the Arctic to the semideserts. In Northern, Middle, and Southern Ural there are more than 10,000 lakes.

In *North Ural*, including Polar, Subpolar, and Northern Ural, there are some 4,300 lakes with a total surface area of about 200 km². The numbers of lakes notably decreases from north to south, in the Polar Ural there are about 3,300 lakes, in the Subpolar Ural there are 820 lakes, and in the Northern Ural about 212 lakes. On the humid western slope there are more lakes (about 2,700) than on the eastern (about 1,600) one. Generally these lakes are small water bodies with areas of about 1–2 km². Only Lakes Big and Small Stchutchie have surface areas of 12 and 4 km², respectively, which are the largest in the Polar Ural having glacial and tectonic origin. The largest lake in the Subpolar Ural by area and volume is Lake Torgovoe (Trading) in Keftalyk, dammed by a moraine, having a length of 2.2 km and width of 0.8 km, surface area 1 km² and depth of 28 m; it is the deepest dammed lake in the Ural. The bottom of the lake is transparent to a depth of 8 m and rich in grayling. Other deep lakes are Lake Muncie of Subpolar Ural (38 m) and Lake Telpos of Northern Ural, surface area 0.25 km², elevation 1,081 m, and depth 49.5 m.

In general, the lakes in the North Ural have a glacial origin in deep corries and cirques. Corries lakes differ by their high elevation (above 800 m) with large depths (up to 20 m) with rounded form on a stony coast almost devoid of vegetation and frequently an absence of fish. In the

valleys there are numerous lakes formed by damming the rivers by moraine: Big and Small Balbaty, Torgovoe (Trading), Dlinnoe (Long) with depths of up to 30 m with an elevation as low as 800 m or even lower. These lakes are rich in fish life, with forest and shrub widespread on the coasts. There are many lakes adjoining the mountains of Northern Ural in the Western-Siberian and Pechora Lowlands. They are located to the east of the Ural Ridge in Lozva, Northern Sosva, Lyapin, Voykara, and Stchutchja (Pike) Basins. To the west of the Ural Ridge, there are not as many lakes, and they are concentrated mainly in valleys and flood-lands of the Rivers Usa and Kara and their inflows. The lowland lakes have areas up to 5 km² and are not very deep (up to 7 m). Thermokarst lakes are distributed along the Ural sides of the Western Siberian and Pechora Lowlands but in the mountains they are rare, especially in the Polar Ural but they occur in the Lake Small Hadata-Ugan Lor basin and in the Big and Small Kary valleys.

Middle Ural is the least raised part of the Ural Mountains and the most populated and industrially active area, with many small lakes, on the order of surface areas 1 km², and of glacial-tectonic origin. The depths of these lakes are small, on the order of 3–5 m. Many lakes of Middle Ural are essentially modified in connection with economic activities in this region.

The following lakes are the largest in the Middle Ural: Lake Tavatuy with an area of 21.2 km², a drainage area of 104 km², a maximum depth of 9 m with outflow River Neiva; Isetskoe Reservoir with an area of 24 km², a drainage area of 600 km²; Lake Shartash with an area of 6.9 km², a drainage area of 41 km², and a depth of 4 m. The water level of Lake Shartash has decreased over the years, and at the beginning of the nineteenth century this depression of the water level was believed to have been due to the construction of branch ducts to supply water to the gold mines. The lake ceased to dry up in 1920. It is now one of the best commercial fishing lakes in the Ural, especially for carp. Because of the lake's shallowness, the lake temperature rises in summer to the extent that the temperature on warm summer days reaches 30°.

The Southern Ural is rich in lakes; in Chelyabinskaja Oblast there are some 3,170 lakes with a total surface area of 2,125 km². Small lakes with the area less than 0.5 km² (about 80% from general number) prevail, though some 100 lakes have the areas greater than 5 km². The lakes stretch in a strip from the Chebarkulskaja Lake group in the south up to Sinarskaja in the north. The largest lakes are Lake Wildy (area 68.1 km²); Lake Turgojak (area 26.4 km², maximum depth 34 m); Lake Yaktykool (area 7.7 km², depth 28 m); Lake Talkas (area 3.9 km², maximum depth 12 m); Lake Irtyash, Lake B. Kisegach, and Lake Kaslinskije. They are the tectonic lakes with great depth, up to 30–40 m.

There are many lakes in the forest-steppe zone of Zauralye. They mainly consist of large water bodies including Welgi, Shablisch, Argajash, B. Kujash, Kaldy, Sugojak, and Tioshki, all of them having their origin as

erosive-tectonic type. The depths of these lakes do not exceed 8–10 m. The karst and flood-land lakes have significant spread also. Karstic lakes usually have small sizes and significant depths (up to 10–15 m and more), but flood-lands are shallow.

The lakes of the Southern Ural are productive. Fish life is rich but it has been disturbed by fish-kills. Nevertheless, there are numerous catfish, carp, pike and perch, bream, and whitefish. More favorable conditions for ichthyofauna are in the lakes of the foothill areas characterized by a stable hydrological regime. Lakes of the Southern Ural are rich in various balneological resources, too (organic and mineral mud, alkaline waters).

The lakes of the West Siberian plain

The West Siberian Plain has an area of some three million square kilometers. It is mainly low-lying and of a boggy nature with an accumulative relief, occupying a part of the Epi-Hercynian platform with large thickness of Mesozoic-Cenozoic sediments.

The climate is typical continental with zones of tundra, a taiga, pretaiga, and forest-steppes or steppes. The area is one of the richest in lakes in Russia, especially in the north. In the Yamal-Nenets district alone there are about 300,000 lakes and in the district of Hunts- Mansiyskiy there are from 200,000 up to 300,000 depending on different estimates. Almost all the lakes are shallow, with areas less than 1 km². In the south of West Siberia, in a steppe and forest-steppe zone, although lakes there are less dense, there are some 10,000, some of which are salt water lakes.

Lakes are of various types, but thermokarst lakes prevail. They are located in tundra, in a zone of permafrost. Most of these lakes are small and of shallow depth. Shallow lakes freeze to the bottom during the harsh Siberian winter and in larger lakes the ice is generally 2 m thick. In the spring in the tundra lowlands, more than half are covered with water; by autumn in some regions the area of the lakes is reduced and some disappear, of which those on the Tazovskiy and Gydanskiy Peninsula are good examples. Along with the small lakes in the Tundra there are some large lakes, for example, Lake Neito (surface area 250 km² and depth 4 m), Lake Jaratto (surface area 150 km² and depth 8 m), and the lakes Jambugo, Jambuto Jaroto, and Hosato.

To the south in the Taiga zone, there are many lakes or "staritsa" (former river bed) in the wide flood plains of the Rivers Ob, Vasugan, Vakh, and others. These water bodies are small, with elongate, arcuate, or falcate forms. In the flood plains of some rivers to the east of the Urals there are lakes or "sory" with surface areas as large as tens of square kilometers, including Vorchato, Voikarskiy Sor, Vanktto, and Big and Small Halce-Lor. Lakes – "Sory" – are located in low lands and in rivers valleys; they have flat hollows and an oozy, fenny bottom; depths are mainly from 1 up to 3 m. Sory fill during spring floods; by the end of summer the water level falls and sory turn to boggy lowlands. The largest lakes of the Taiga zone, with areas exceeding 30 km² include

Shuryshkaraskiy sor, Kondinskiy sor, Big and Small Soviet, Makovskoe and Nalimie, Nunto, Pjakuto, Chaselskoe, Chertovo, Tormentor, Vandmtor, Untor, The Big Sor, Syrkovoe, Tursunskiy Tuman, Leushinskiy Tuman and Pelymskiy Tuman, Jahtur, and Temrjak.

There are an abundance of lakes of various sizes in steppe and forest-steppe areas whose formation is related to relief features and water balance. In conditions of flat relief and large losses to evaporation the majority of lake basins are endorheic. Melted snow waters play the main role in feeding the lakes. At the same time, ground water has essential value, especially for large lakes. The number of lakes is estimated in thousands, probably more than 11,000 in Altai alone. It is convenient to summarize the following main groups:

1. The lakes of Kulundinskaja steppe include the largest salt-pan Lake Kulundinskoe, surface area (728 km²), Lake Kuchukskoe (181 km²), Bolshoe Topolnoe (Big Poplar) (77 km²), and Bolshoe Jarovoe (Big Spring) (68 km²).
2. The lakes of Ishimskaja steppe include a number of small reservoirs between the Rivers Irtysh and Ishim, the largest being Lake Bolshoy Uvat, Kartabyz, and Malyi Donki.
3. The lakes of Zauralye include many shallow steppe reservoirs of the Chelyabinsk and Kurgan areas, Lakes Mamynkool, Welgi, Butash, Kartabyz, Malyi, and Donki.
4. Lakes of Priobskoe Plateau including Lake Gorkoe (Bitter), surface area 140 km².
5. Lakes of Barabinskaja steppe including Lakes Chany (surface area 1,900 km²), Ubinskoe, Sartlan, Tandova, and Urum.

Saucer-shaped hollows of lakes are flat and are poorly visible on the plain. Their sizes change extremely depending on season. Lakes are large in the spring and small in the summer; many lakes dry up at this time. Lakes water is characterized by high mineralization; some lakes are hypersalt. Their salinity can exceed 100 g/l. The largest salt lakes are Kulundinskie, Mihajlovskie, Petuhovskie, and Borovye. The Kulundinskie lakes produce some 350 million tons of table salt annually. The greatest in this group is Lake Kulundinskoe, with a surface area of 728 km². Lake Malinovoe has a crimson shade of water.

Studies since the seventeenth century have shown that some lakes in the south of the West Siberian Plain are in continuous drying with changes of outline and size. A typical example is Lake Chany, the largest lake in this region located between the Rivers Ob and Irtysh in Barabinskaja Lowland on the border of steppe and forest-steppe zones. Lake Chany has a complex configuration consisting of two parts. The first includes the Big Chany Lake, whose structure includes Yarkovskiy, Tagano-Kazantsevskiy, and Chinjaihinskiy Reaches and Lake Yarkool connected with Big Chany by two channels about 1 km in length with the flow into the Chinjaihinskiy Reach. The second part is the Small Chany Lake

connected with the Chinjaihinskiy Reach by Channel Kozhurla, about 7 km in length. The changes in water level of the lake have been recorded since 1899 as follows:

An increase in water level took place between 1900 and 1914 (rise of 2 m) and between 1937 and 1950 (rise of 2 m). A reduction in water level and surface water area took place between the periods 1914–1937 and 1950–1970. In 1972 the construction of dams through the group of islands Udinskiy Reach separated the above parts of the lake. This allowed the reduction of losses by evaporation and raised the water level in the east part of the lake by 0.5 m. At the same time, however, the Udinskiy Reach inflow started to dry up and within 6 years the water level went down 1.1 m, progressively drying up the Udinskiy Reach until today.

The water balance of Lake Chany depends on precipitation and evaporation. However, it is believed that global warming has already had an effect on the long-term regime and on its drying over the past 100 years. At the end of the nineteenth century the area of the lake was 3,170 km; by the end of the twentieth century it had decreased to 1,707 km. Reduction of the surface area resulted in a change in temperature and oxygen in its water mass. The anthropogenous influence on the lake has consequently resulted in a deterioration of the water quantity and quality. The drying up of Lake Chany, as well as other numerous lakes of the Barabinskaja Lowland, continues.

Lakes of the Altai-Sayan Mountains Country

The Altai-Sayan Mountain country includes the high ridges of Altai (4,506 m), Mongolian Altai (4,362 m), Western Sayan (2,930 m), East Sayan (3,491 m), Hangai (3,905 m), and deep tectonic depressions. This mountain country appeared on Paleozoic structure revived by new tectonic movements. It is located on the border of typical and sharply continental sectors of Asia, with landscapes characterized by great variety and contrasts. On Altai the present glaciation is considerably advanced. The Altai-Sayan mountain country is rich in lakes. There are more than 15,000 in total. About 6,700 are in Tuva, about 7,000 in Altai, and about 300 in Hakassja. In the Teletskoe Basin there are some 2,200 small lakes. The area of lakes in Altai amounts to 600 km² and in Tuva about 1,100 km². These lakes have tectonic, glacial, dammed piping, and karstic origin. The largest lakes in Altai are Teletskoe and Dzhulukol. Among the largest lakes of the Sayan Mountains are Lake Noyon-Holl, Tere-Holl, and Lake Todga (Azas). Small mountain lakes prevail both on Altai and in Sayan.

Lake Teletskoe is the largest lake in Altai-Sayan with details as follows:

- (a) Tectonic depression processed by glaciers and filled with water
- (b) The lake consists of two parts – the north part of length 28 km, and the south part of length 50 km
- (c) Elevation 473 m
- (d) Width 3.2 km

- (e) Surface area 230 m²
- (f) Volume 40 m³
- (g) Maximum depth 325 m (one of the deepest in Russia)
- (h) Seventy percent of inflow, River Chulyshman
- (i) Outflow – River Bija
- (j) Evaporation loss of the order of 2%
- (k) Water level fluctuation 4–5 m, minimum in March, maximum in June–July
- (l) Transparency 6–12 m
- (m) Mineral and organic substances 80 mg/l
- (n) pH 7.3–7.6
- (o) Ichthyofauna is represented by 13 species including *Hucho* spp., whitefish, grayling, pike, minnow, perch, and eel-pot.

Both on Altai and in the Sayan Mountains there are large numbers of small lakes whose origins are from glacial activity such as the cirque lakes and moraine dammed lakes. The latter are located in the glacial valleys; their depths range from 7 to 10 m but large lakes have depths of several tens of meters. Lake Taymenye in Altai has a depth of 68 m. Lake Toga is a large glacial lake in the Sayan Mountains with a length of 20 km, a width of 5 km, and a depth of 100 m. While another, Lake Nayon-Holt, is some 225 m deep. Among the other largest mountain lakes are Lakes Uzun Kool, Yerri Holt, and Hindiktig-Holt. Most of mountain lakes are covered by ice from the end of September until the end of May. The feed is from melting glaciers. Thawed water brings silt, resulting in the white color of some lakes. For example, a bucket of water from Lake Ak-Kemskoe and others usually has a 5 cm layer of viscous bluish glacial silt.

Some lakes in Altai-Sayan have also been formed by internal erosion of Karstic origin. The beautiful Lake Ajskoe, for example, located on an ancient terrace of the River Katun at an elevation of 280 m, was formed in Upper Quaternary 20,000–25,000 years ago. The lake has a surface area of 87,500 m² and a maximum depth of 20–25 m. Lake Ajskoe is a national protected body. A number of fresh and saline lakes were formed in the lowered parts of the Tuva Hollow. Lake Chagytay, a large and the deepest fresh water body, is located here, with a surface area of 28.5 m², an elevation of 1,003 m elevation, and a maximum depth of 19 m. The lake is rich in fish such as ide, pike, bream, and carp. A significant number of lakes is situated in the top part of Yenisei basin, in the so-called Minusinskaja Hollow. Here also there are lakes with high mineralization of waters.

Many of Sayan lakes, for example Tuva lakes Svatikovo, Hadyn, Dus-Holl, Cheder, By-Holl, Shara-Nur, and Lake Azas, are famous for medical purposes, for instance, medical mud. One of the largest of them is the highly mineralized Lake Shira in Hakassija. Approximately 380 million cubic meters of medical highly mineralized water is concentrated in this lake. Another interesting water body is the saline lake Tus. Originally it was estimated that the salt content of the lake amounted

to 250 g/l, similar, in fact, to the Dead Sea. In the twentieth century, salt was extracted from this lake. After desalination, which is now taking place, the salt content has decreased to 155 g/l.

The lakes of Eastern Siberia

Eastern Siberia includes the North Siberian Country, Northeast Siberia, and the Central Siberian Plateau. The climate is extremely continental, arctic, subarctic, and boreal and sharp permafrost is distributed in all regions. There are tundra, forest tundra, and taiga and north taiga landscapes.

The North Siberian Country includes the North Siberian Plain, Byrranga Mountains (1,146 m), and the Northern Achipelago. Northern Siberia is mainly mountainous folded structures with the highest mountains Verkhojanskiy (2,389 m), Santar-Hajata (2,959 m), and Cherskogo (3,147 m). The Central Siberian Plateau lies on the Precambrian Siberian Platform. Heavy lava masses lie in the northwest (Plateau Putorana 1,664 m). Eastern Siberia is the richest lake region in Russia. In total there are more than 1,300,000 reservoirs. In Yakutia there are some 700,000 lakes and another 300,000 in Krasnoyarskiy Kray.

In Northern Siberia there are some 100,000 lakes, mainly consisting of small lakes in Pripoljarnomorskaja Lowland and along the marginal seas of the Arctic Ocean. The numerous small lakes of Yano-Indigirskaja and Kolymskaja Lowlands occupy about 9% of the total area of these regions. They are better known by the local name “layd.” Other small but numerous lakes, known as “lyby,” are located on the deltic islands of the Rivers Lena, Yana, and Indigirka. The majority of the lakes have a thermokarst origin and suffer from the thawing of buried ice with significant distribution in the Pripoljarnomorskaja Lowland. As a rule, thermokarst lakes have an oval or round shape, and the lakes formed in a riverbed have a lengthened form. Almost all lakes are shallow, the depth seldom exceeding 4 m. More lakes are connected by channels. The lakes are covered with ice from October until June; many lakes freeze to the bottom, which results in fish killing.

The largest lake in Northern Siberia is Lake Taimyr. Lake Taimyr, located north of the polar circle in the center of the Taimyr Peninsula at the foot of Plateau Byrranga, has a surface area of 4,560 km². The lake is shallow, having an average depth of 2.8 m but with a maximum depth of 26 m. The River Upper Taimyra flows into the lake and the River Lower Taimyr flows out of the lake to the Karskoe Sea. The lake is ice free for only 3 months of the year and during the arctic winter the ice reaches 2 m in thickness. Generally, about 80% of all the lakes freeze to the bottom. Lake Taimyr is rich in fish life, whitefish, eel-pot, grayling, omul, and Siberian goby, and birds include swans, geese, ducks, rough-leg buzzards, falcons, and peregrines. The birds spend the winter in the warm countries, but return to the area annually.

The other largest lakes in Northern Siberia include Kungasalah, Portjagino, Labaz, Kokora, Pronchistcheva,

Ajaturkuna (Taimyr Peninsula); Kieng-Kuell, Sappja (North Siberian Plain); Bustah, Orotko, Solungah, Mogotoevo, Omuk-Kuell, Hantagay, Dolgoe (Yano-Indigirskaja Lowland); Ozhogino (Abyjskaja Lowland); Ilyrgytgyn, Bolshoe Morskoe, Nerpichie, Ruzhnikova, Abe and Ulahan-Abe (Kolyma Lowland). The above lakes in Northern Siberia are located in an extremely sparsely populated area and their water quality remains practically pristine.

Northeast Siberia is also rich in lakes, especially in Anadyrskaja Lowland, which are usually small in size and shallow in depth. They have small sizes and insignificant depths. Their origin is mainly connected with the processes of frosty erosion and glaciations, but there are floodplain and tectonic lakes, too. Among the best known lakes in this region are Lake Krasnoe, with a surface area of 660 km², Emanda, (Plateau Janskom), Labynakyr, Alysadah (Ojmjakonskoe Plateau), and Malyk (Nerskoe Plateau). Along the coasts of Chukchi and the Bering Sea are a large number of large lagoons, notably Lake Lavrentija one of the largest.

Another beautiful lake in this area is Lake Elgygytgyn in Chukotka in the Anadyrskoe Plateau. This lake is deep bowled, with an 18 km diameter, and has a dense ultramarine color and a huge depth of 467 m and, contrary to the laws of physics, warm water lies below the cold water layer. The lake is rich in fish, with five different kinds of salmon.

Thermokarst lakes are typically found in the *Mid-Siberian Plateau* where their origin is connected with permafrost, particularly in the Lena- Viljuiskaja Lowland where fossil are found (buried) in ice. Most of these lakes are widely spread across the region and have the characteristic round shape. The lakes are young, being formed over a short period of time on the order of tens of years but they often dry up and disappear. This is particularly observed in the Lena-Amginskiy catchment area. At the beginning of the twentieth century there were hundreds of dried up lakes here. Along with the lakes drying, numerous cases of repeated filling have been observed also. There are many such lakes that gradually vanish and then periodically fill with water. In addition to thermokarst lakes, there are floodplain, tectonic, and glacial-tectonic lakes.

One of the most interesting lake areas in this region is Plateau Putorana with 20,000 lakes, over 100 of them having surface areas exceeding 1 km² and 18 lakes with surface areas exceeding 50 km². The best known is Lake Hantaiskoe, having a surface area of 1,560 km² and a depth of 420 m, and Lake Pyasino with surface area of 735 km². The hollows of these largest lakes by their origin are considered to erosional-tectonic type with glacial treatment. Their formation occurred in the Neogene, and even during the glacial epoch they did not become covered completely by ice. Hydrology of these lakes shows that the feed to the lakes comes from snow to the extent of 50%, the remainder coming from rain and groundwater. The duration of the ice cover depends on the size of the lake and depth.

On average it lasts for 211–248 days and on large deep lakes ice cover starts in November to the first days of December. The thickness of the ice depends on snow deposits but maximum thickness generally occurs in April before the thaw in mid-May to the end of May and reaches thicknesses of about 1.15–1.20 m. The period of opening (or ice break) generally takes from 10 to 20 days and ice cover is finally cleared by the beginning of July. The temperatures of large mountain lakes are above zero from May until October/November with maximums occurring in July with values of 8–9°C in shallow lakes and 4–5°C in large deep water lakes.

Finally, Eastern Siberia has a distribution of both fresh and salty lakes. For example, in lakes of the Vilyui Basin (Kempendjaiskie), the extraction of salt has been carried out for many years. The ecological condition of the majority of Eastern Siberia lakes is safe enough, however, some lakes of Plateau Putorana experience significant anthropogenic loading.

Lakes of the Baikal Mountain Country

The Baikal Mountain country is in the southeast of Siberia. The country comprises block mountains, elevation 2,999 m, aged from Precambrian to Mesozoic, combined with crystal rocks. The climate is sharply and extremely continental, the northern part being situated in a taiga zone, the southern in a steppe zone.

There are some 1,000 lakes in this region, in territory of Irkutsk district alone there are about 4,000 lakes. The best known is Lake Baikal, which is second only to the Caspian Seas. The following facts describe Lake Baikal:

- (a) Surface area 31,500 km²
- (b) Volume 23,000 km³, 22% of world reserves
- (c) Length 676 km
- (d) Average width 48 km
- (e) Depth 1,741 m, making it the deepest in the world
- (f) Elevation 1,285 m
- (g) Catchment 557,000 km²
- (h) Evaporation 6%
- (i) Water level characterized by small fluctuations 20–144 cm, highest in September and lowest in April
- (j) Seiches amplitude of level fluctuation 12–14 cm.
- (k) Temperature of water in benthonic layers 3.1°

The history of Baikal goes back 25 million years. Its origin is dominated by global rift structure and high seismic activity. Recent geophysical research has shown that Baikal may be an incipient ocean based on the speed of the dispersion of the banks by 2 cm per year, which is how continents have dispersed in Africa and South America. There are 22 small islands on the lake, the largest of which is Olkhon Island. In morphological respects, the lake can be divided into three basic hollows

1. Northern, having greatest depth over 983 m
2. Southern, greatest depth 1,436 m
3. Middle, greatest depth 1,741

The lake is fed by 336 rivers, the largest of which is River Selenga, whose catchment is almost 83% of the total catchment. The single outlet is the River Angara. In 1959 the Irkutsk hydroelectric station was built by damming the river at the outlet, whereupon, water level of the lake was raised by approximately 1 m.

The chemical composition of the lake water is as follows:

1. Water has weak mineralization
2. Water is soft
3. Average sum of ions about 95 mg/l
4. Average transparency 26 m maximum 40 m.
5. Color varies by place and season – dark blue with transparency 30 m
6. Significant changes of lake temperature within a year affect only the top 200–250 m
7. The period of autumn circulation begins with a decrease in temperature of the top layers of up to 4°

Lake Baikal freezes late – in January and in winter, with conditions of sharp temperature fluctuation, numerous cracks, from several millimeters up to meters in width, form on the ice cover. Some of them are formed in the same place every year. The lake is opened only in the middle of May. Because of its unique depth, many scientific investigations are, and have been, carried out. In the case of fauna, it is known that 60% of 2,630 kinds of animals (1,550) and plants (1,080) living in the lake are endemic. Among them are golomyanka fish, seals, and omul.

Among other large lakes in the Baikal Mountain country are Bolshoi Eravnoe, Arahley, Baunt, Busany, Oron (Vitum River Basin), Gusinoe and Selenginskoe (Selenga River Basin), Oron (Irkutskaya Oblast), closed Lake Zoon-Torey, and Barun – Torey (near Mongolian border).

There are few lakes north of Vitimskiy Krai in Patomskoe and North-Baikal Plateaus. Their number rises from North-Muiskiy Ridge and, further to the south, on Vitimskoe Plateau. There are about 500 lakes in the River Vitim Basin. They can conveniently be divided into two groups: Valley lakes in wide valleys, mainly in Muisko-Kuandinskaja, and Bauntovskaja Hollows. Some lakes here have arisen as a result of tectonic hollows filling with water. Among them are the large Tsypa-Tspinskaja and Eravno-Harginskaja lake system. The largest lake of the group, Baunt, is located in Bauntovskaja Hollow in the system of Verhnjya (Upper) Tsypa, Tsypican, and Nizhnjya (Lower) Tsypa Rivers. It has a triangular shape with length about 16 km and width 9 km. The maximum depth is 33 m and the transparency is 3.5 m. An interesting feature of Bauntovskaja Hollow is the presence of a large number of hot sources (for example, Mogoyskiy Tochinskiy, Busaniyskiy). Lake Baunt is rich in fish such as “soroga,” perch, crucian, whitefish, ide, and eel-pot, and sometimes sturgeon and grayling. It is interesting to note that recently a Baikal goby has been found that was believed to have only been in Lake Baikal. It is also interesting that it is believed that more than a million years ago,

in the second half of Tertiary or at the beginning of Quaternary, there was a connection between Baikal and Baunt Lakes or that they may have been a single whole.

The largest lakes of the Eravno-Harginskoi system is Lake Big Eravnoe near the Vitim River Basin on a catchment with the Selenga River. The lake has a length of 14 km, a width of 13 km, and a depth of 5–15 m. The banks are low and covered by dense bush of cane. The lake is rich in fish, mainly pike, crucian, and perch.

Many small lakes are scattered in the Muiskaja Valley and it is reported that research has shown that all the small lakes were once one large reservoir that emptied when Vitim broke through ridges to the north. In Southern-Muiskaja Ridge there is Lake Dorong, resting in a narrow deep rocky crevice connected with the Verhnjya (Upper) Tsypa River. Lake Dorong is at elevation 1,110 m and 11 km long and 1 km in width along its full length. The lake water temperature is 6–10° and the maximum depth is 55 m.

Mountain lakes of glacial origin were formed by moraine dams left behind by glaciers. Some of them are the source of rivers or streams. Many lakes lay above a timberline. The largest is Lake Dorong and a system of Amudisskiy Lakes. In addition to these lakes is Lake Oron, located at the foot of the northern slopes of North-Muiskiy Ridge on the right bank of the Vitim River. The lake is connected by a 1 km passage to the river. The lake has a length of 19 km, a width of 2.25 km in the southeast, and 6.5 km in the northeast part. The bottom of the lake falls abruptly on the southern side, where the depth reaches 184 m.

Lakes of Shilka and Argon Basins represent, in most cases, the remainder of a now-vanished large water bodies. Among them there are dried up lakes such as Zoon-Torey (surface area 258 km²) and Barun-Torey (surface area 528 km²), located in the south on the border of Russia and Mongolia. Some lakes in the Argun River basin are mineralized through dry climate conditions. There are also salty and bitter-salty lakes. The salt composition of the lake waters of Doron, Onon, and Borgaiskoe contain soda because the rocks are basically igneous. Lake Doron has long since been a source of the extraction of soda. Soda lakes, in freezing, evolve a crystal soda that looks like a milky white color on ice. There are a group of bitter-salty lakes in the Chita area and Borzinskiy lakes. In the southern part of the River Argun Basin between two rivers (Agi and Onon) the group of Aginsky Steppe lakes represent shallow, saucer-shaped hollows filled with water, some of them drying up in summer. There are also many shallow lakes in the River Amur flood plains. In winter many of them completely freeze.

The ecological condition of most of the lakes network of the Baikal Mountain Country is generally good. Lake Baikal of course attracts a great deal of attention from specialists, academics, and tourists. The main lake pollution is connected with Rivers Selenga and Upper Angara (about 2/3 sulfates, more than 80% chlorides, and 70% organic substances). The pollution was caused by paper and pulp,

chemical, and petrochemical industries. Waters coming from Mongolia have higher content of mineral oil and ions of copper and phenols, all many times above the maximum concentration limits.

Lakes of Priamurie

Priamurie is a part of Priamuro-Korean, noted for its mountain relief with vast mountainous depressions on the Paleozoic and Mesozoic structures. The climate is from monsoon to sharp continental, and taiga landscape gives way to pretaiga and deciduous Far Eastern landscapes. There are some thousand lakes, mostly small but large lakes are found in the valleys of the Rivers Razdolnaya and Ussury and on the Prikhankayskaya Plain.

The largest lake of Priamurie is Lake Khanka, located in the Ussuri Basin on the border of Russia and China. Its surface area is about 4,100 km² and catchment 16,890 km² with 15,370 km² in Russia, the remainder in China. The lake is shallow with a mean depth of 4.5 m and maximum of 10 m. The River Sungacha, a tributary of the Ussuri, issues from the lake. Lake Khanka has abundant vegetation consisting of various species of sedge and reed and is well known for the migration of water fowl, of which there are about 300,000–350,000 ducks, 100,000–130,000 geese, and 3,000–5,000 swans; rare species of Japanese cranes (20–25 families), Daurskia cranes, 10–15 families of far eastern white storks, and Bera porchard also have their nests in the Khanka Basin.

Among other large lakes with a surface area more than 100 km² are Lakes Chukchagirskoe, Bolshoe Kizi, Orell, Udy, Everon, Bolon, Hummy, and Chlya. Their basins represent fault depressions with alluvial deposits. Most of the lakes are of shallow depths not exceeding 3–8 m and most are connected by channels to the Amur River. The significant part of Priamurie lakes is located near the sea and has saltish or salty water.

The condition of Priamurie lakes and their catchment has considerably worsened in recent years due to industry and chemical pollution. Other problems include land tenure and the degradation of a soil-vegetation cover over water-marsh grounds. Rice growing in the areas of Prikhankajskaja Plain is a powerful spur to the economy and crops have significantly increased over the past 10 years. Unfortunately, this has meant considerable amounts of fertilizers over the catchment of Lake Khanka leading inevitably to deterioration of the lake water quality due to elements of copper, zinc, phenols, and mineral oil and pesticides.

Lakes of the Kamchatka-Kuril

The Kamchatka-Kuril country is part of the Pacific Ocean folded zone in which tectonic movement still continues. Kamchatka at the elevation of 4,750 m has a volcanic origin and the Kuriles Ridge contains a series of volcanoes, where the glaciation is advanced. The Kamchatka Peninsula has a large variety of lakes of glacial and floodplain origin. Sea lagoons are found in the coastal areas but the most exotic lakes are of volcanic origin where the craters

have been filled with water. Examples are the large volcano-tectonic lakes of Kamchatka – L. Cronockoe, surface area of 245 km², depth 306 m, and L. Kurilskoe, surface area 77.1 km² and a depth of 128 m. Along the Pacific coast are the following lakes: Karymskoe of volcanic origin with a water surface of 10.3 km², Bolshoe, Kalygar, surface area 5.0 km², Bolshoe Medvedka, surface area 5.0 km², Ostrovnnoe, surface area 5.4 km², and Nerpichje, surface area 13.2 km². Each of these lakes has unique beauty and aquatic inhabitants. The banks are steep or flat and covered with rich vegetation. The lakes are pristine with red salmon, blue-black salmon, roach, and keta.

The main characteristic of volcanic lakes is the presence of power and material balance of a hypogene source, which may have a significant influence on the hydrodynamical and hydrochemical processes of the lake. In this connection, a number of volcanic lakes comprise concentrated acid instead of water. For example, the volcanic lake Malyi Semenchak in Troitskogo. The temperature of this opaque lake ranges from 27° to 42° in a solution of sulfuric and hydrochloric acid of middle concentration. The dimensions of the lake are somewhat surprising, having a width of 0.5 km and a depth of up to 140 m. There is a strong suspicion that the lake has suffered a recent eruption. Another lake, Lake Karymskoe, suffered the effects of an eruption to the Karymskiy volcano only 6 m away. The eruption lasted 18–20 h and caused 100 underwater explosions in the lake, creating a “tsunami” with waves as high as 15 m. The lake literally boiled and all life in the lake was lost. The lake is probably the largest acid lake in the world. In a valley of the upper and middle courses of the Kamchatka River there are the small spring-fed lakes (Domashnee, Ushki, etc.); their occurrence is connected with lava-flows.

The plant life in Kamchatka lakes is fascinating, with algae and organisms living in a burning solution. Nevertheless, numerous colonies of multicolored thermophilic organisms float on a surface of hot lakes with temperatures of 30–70°. The life of fresh lakes is multiform also, for example, swans are able to live here.

The various flora and fauna of volcanic lakes frequently participate in a biogeochemical cycle of substance and layers of the ashes introduced from other volcanoes are found. In bottom sediments there is an accumulation of many chemical elements, and highly mineralized waters quite often represent liquid ore. Many lakes are rich in medical mud due to microbe processing of vegetation. Lakes Utinoe and Sakscoe have each about a meter layer of medical hydrosulfuric mud.

Lagoon lakes often formed at the mouths of rivers but generally elongate in parallel with the coast. These lagoon lakes are rich in bird life and fish such as flounders from sea entry, starfish and jellyfish, and an abundance of salmon from the sea concentrating in estuaries and river mouths. The greatest of them is shallow Lake Nerpichje (the area about 500 km²), located in a mouth of Kamchatka River. The largest estuaries on the Pacific

coast are Zhupanovsky, with a surface area of 24 km², and Semjachiksky, with a surface area of 10 km². On the Bering Sea coast are the following lagoons: Malamvajam, Ukinskaja, Haylulinskaja, Ivashkinskaja, Makarievskaja, and Kaum. On the Okhotsk Sea the following estuary-type lagoons, Mikojanovsky, Brumka and Moroshechnaja. Lakes Nizovtcevo, Krasikovskoe, Azabachie, and Kursin, have been formed as a result of the transfer of river alluvium from the Kamchatka River.

In Kuriles, there are some hundred lakes of various origin, some due to volcanic activity. There are small, deep mountain lakes occupying craters of extinct volcanoes. For example, Tomari-Yama on Kunasiri Island, Lake Usen-Ko on Krenitcina peak, having a depth of 200 m, and others. Waters of these lakes have yellowish color because of sulfuric sources inflow. The coast is occupied by larger lakes, usual lagoons type, with length up to 10 km. They are normally connected to the sea by small channels. The coast of Sakhalin Island abound in lakes or lagoons separated from the sea by narrow spits. Some lakes that have been cut off from the sea have become fresh water bodies.

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Cross-references

[Baikal, Lake](#)
[Caspian Sea](#)
[Ladoga Lake and Onego Lake \(Lakes Ladozhskoye and Onezhskoye\)](#)
[Russian Lakes](#)
[Russian Lakes, Geographical Classification](#)

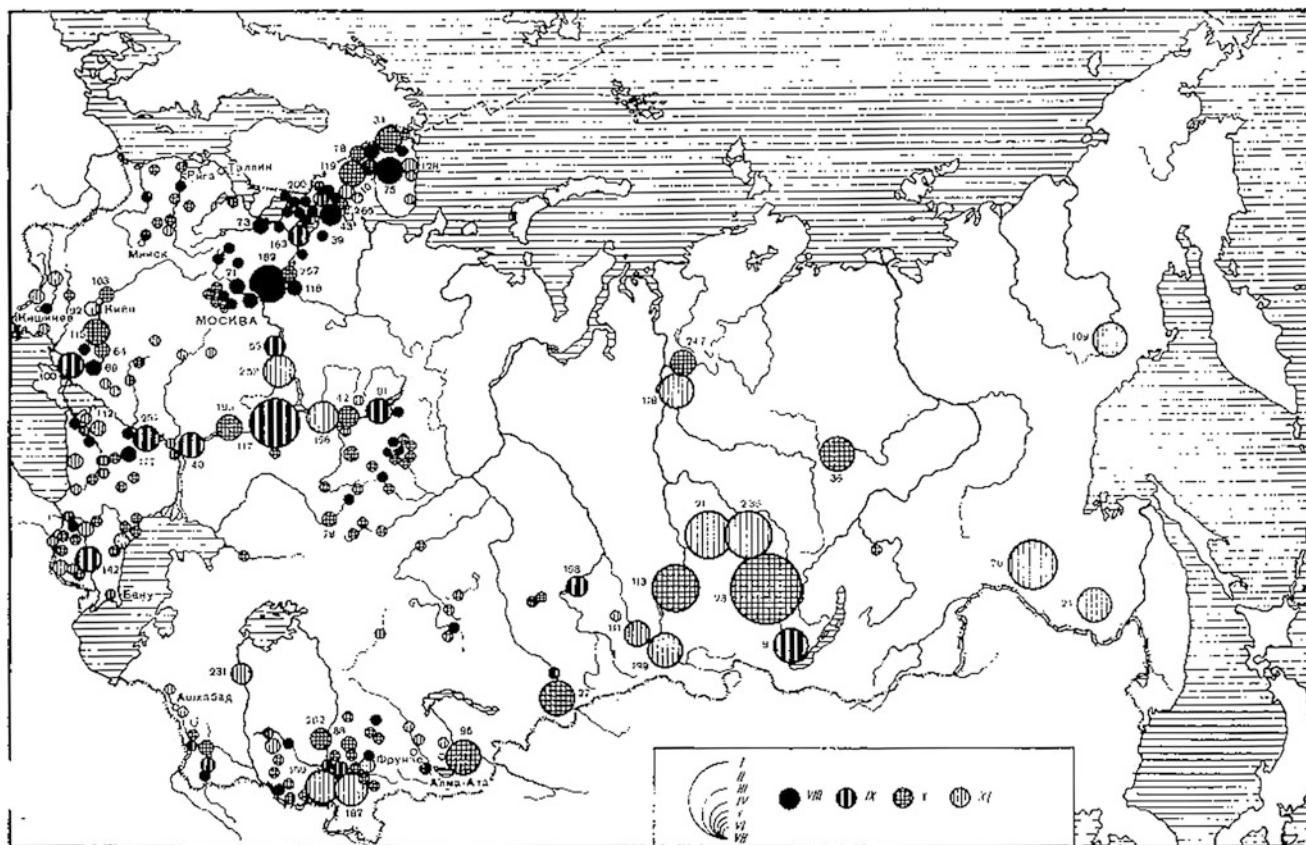
RUSSIAN WATER RESERVOIRS

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Description

Water reservoirs of Russia are artificial water basins more than one million cubic meters in volume. Ponds are artificial water basins less than one million cubic meters in volume. The first water reservoir in Russia is the Alapayevsk reservoir, which is five million cubic meters in volume and 2 km² in area. It was constructed in 1704 on the Neiva River in the Urals. During the period from the eighteenth to the beginning of the twentieth century several dozens of small water reservoirs were built for industrial water supply ([Figure 1](#)).

Large-scale construction of water reservoirs started in the second half of the twentieth century, after the Great Patriotic war (1941–1945). However, even before the beginning of the war, two very important water reservoirs were built. The first one was the Ivankovsk reservoir – the main source of water supply for Moscow (60%), built on the Upper Volga in 1937. The dam of the reservoir is located in the area of the town of Dubna. The second was the Rybinsk reservoir on the Volga River regulating the river runoff of the Upper Volga. It was filled up to the design reference marks during 1941–1947. In 1941, when there was real threat of fascist occupation of the Russian capital, the Rybinsk hydroelectric power station was the sole source of electric supply for Moscow.



Russian Water Reservoirs, Figure 1 Reservoirs of Soviet Union (1979). The contemporary scheme of Russia's reservoirs is absent. I – reservoirs' volume more than 100 km³; II – 50–100; III – 25–50; IV – 10–25; V – 5–10; VI – 1–5; VII – 0.1–1 km³. The periods of construction of the reservoirs: VIII – before 1951; IX – 1951–1960; X – 1961–1970; XI – after 1970.

Large-scale construction of water reservoirs occurred during the 1950s–1970s of the twentieth century. It was carried out in the European part of the country in the framework of the well-known plan of the State electrification of Russia developed by the Russian specialists in the beginning of the twentieth century, even before the October revolution of 1917.

In 2010, there were about 2,700 water reservoirs in Russia, each more than one million cubic meters in volume, and 26,300 lb. From the total number of water reservoirs there were 252 reservoirs more than ten million cubic meters in volume, and 86 artificial water basins more than 100 million cubic meters in volume. There were 49 large water reservoirs of federal (state) importance, more than 1 km³ in volume each. These are mainly the reservoirs of Volga-Kama and Angara-Yenisey cascades, as well as lake-reservoirs, where the useful regulated volume of water is provided through the increase of water level in lakes by means of hydraulic engineering constructions.

The share of Russia's water reservoirs in the modern world fund of artificial reservoirs amounts to 14% by total volume and 16% by the total area. Parameters of Russia's

reservoir fund (total volume, active capacity, area) approximately correspond to those of the USA.

Russia is in the top ten countries of the world with the biggest number of constructed dams and, correspondingly, of water reservoirs. These ten countries include USA, Canada, China, Brazil, India, Turkey, Spain, France, and Japan.

Total volume of the water reservoirs in Russia amounts to nearly 1,000 km³, active capacity is 435 km³, the total area of the water surface is 115,400 km², including 52,400 km² of the lake areas where the water level is raised artificially by means of hydraulic engineering constructions. Total length of the Russian water reservoirs' coastline is 60,000 km, which is 1.5 times more, than the coastal line of the seas washing Russia (40,000 km).

Water reservoirs in Russia are irregularly distributed by the economic regions of the country. There are 72 reservoirs in the Northern economic region, 32 ones in the Northwest, 206 in the Central region, 74 in the Volga-Vyatka region, 575 in the Central Black Earth region, 612 in the Volga region, 408 in the North-Caucasian region, 394 in the Ural region, 121 in the West-Siberian

region, 68 in the East-Siberian region, 79 in the Far Eastern region, and 9 in the Kaliningrad region.

The water reservoirs constructed on the rivers are more widely distributed, as well as lake-reservoirs. The highest degree of the river flow regulation is in the rivers of the European territory of the country where the water-consumers and water-users have deficiency of water resources during some periods and years. Currently, 40% of the Volga River, 50% of the Don River, and 68% of the Ural River flow water is regulated by reservoirs. Total active capacity of the regulated flow of the rivers in the European part of Russia amounts to 161 km³, including 35 km³ on the rivers of northern, and 126 km³ of the southern watershed slope.

The whole modern fund of the country's water reservoirs was built within the period of existence of the USSR (Union of the Soviet Socialist Republics, 1917–1991). Large-scale hydraulic engineering construction, including building of water reservoirs, in Russia is caused by the fact that rivers in their natural condition cannot satisfy the increased economic and social needs for water supply. Construction of reservoirs in the most developed part of the country (southern, central, and northwest regions of the European part of the Russian Federation, the Ural region, the Caucasus) is caused by the fact that these regions are supplied with insignificant part of resources of river runoff. Irregularity of river runoff by seasons of the year and between the years also exists.

The most developed economic regions of the country occupying 27% of the area of the Russian Federation are supplied with about 4% of water resources. In many regions of Russia more than half of annual runoff happens in two–three spring months, and the runoff of low water years is much less (up to three times) of the average annual.

Parameters of Russian water reservoirs widely vary: capacity ranges from one million cubic meters to 169,000 million cubic meters, area – from 1 km² to 5,900 km², length – from 1 km to 565 km, depth in the dam parts – from 10 m to 150 m, and width of large reservoirs in Russia reaches 35–40 km.

Large reservoirs in Russia are mostly used in a complex – for the sake of water-power engineering, thermal engineering, atomic engineering, irrigation, industrial and economic-potable water supply, water transport, fishing industry, and recreation. In 2010, about 400 hydroelectric power stations operated in the country, 118 of them have capacity more than 25 mW. The share of hydroelectric power stations in the generation of electric power in Russia amounts to about 20%. Total capacity of hydroelectric power stations in Russia amounts to about 45 million kW. Approximately 100 reservoirs provide water for thermal and atomic power stations generating hundreds of billions of kilowatt-hours. Forty-four of them, with total capacity more than 50 gW, provided with special cooler reservoirs, develop 350 billion kilowatt-hours of electric power. Hydropower potential of Russia amounts to 850 billion kilowatt-hours, which is second largest in the world after China, though the degree of

its exploitation in Russia amounts to 19%. In the European part of the country it is exploited on 50%, in Siberia – on 10%, and in the Far East only on 4% (Table 1).

In Russia 18 million hectares of the soil is irrigated, 8 million hectares of which – on the basis of the reservoirs' water resources.

Total extent of internal waterways of Russia amounts to about 140,000 km, while that of the water reservoirs is 12,000 km. Construction of water reservoirs in Russia allowed to radically reconstruct the waterways on the main navigable rivers (Volga, Kama, Don, Yenisey, Angara). Construction of water reservoirs allowed to form the uniform deepwater system of waterways on the European territory of the country, with the guaranteed depth of 3.4 m, and made it possible to use large-capacity vessels with displacement up to 5,000 t.

Almost half (45%) of the total volume of water reservoirs in Russia and one third of the water surface area (35%) is in Siberia and the Far East, where very large and the world's largest water reservoirs have been constructed (Bratsk, Krasnoyarsk, Boguchansk, Baikal, Sayano-Shushensk, Ust-Ilimsk, Zeysk, Viluyusk, Novosibirsk reservoirs).

Energy was the main decisive factor in creation of large water reservoirs in Russia. After the end of the Great Patriotic war (1945) there was the sharpest need to increase the production of electric power for restoration of the national economy that was destroyed on 60–80% during the war. The chosen way was construction of heavy-duty hydroelectric power stations on the large European rivers of the country – Volga, Kama, Don. For a number of technical and economic reasons in 1950s–1960s of the twentieth century thermal engineering could not develop adequately fast in Russia. The atomic engineering at that time only started to be formed as power branch. Powerful hydroelectric power stations and large water reservoirs were created on the plain rivers of the European part of the country. Design development and creation of large hydroelectric power stations in Siberia on the rivers with high hydro-energy potential were carried out simultaneously, first of all, on the Angara and Yenisey.

Construction of water reservoirs in the European part of the country had a complex orientation – production of electric power, improvement of water transport operating conditions, industrial and municipal water supply, flood control, fishing industry, and recreation. The highest population density is on the Russian plain where 60% of the population of Russia resides on the 12% of the country's territory; about 70% of Gross National product is manufactured in this region. The water reservoirs created in the European part of the country provide industrial water supply for metallurgical, chemical, pulp and paper, and energy branches of economy. Water cargo transportation on the united deepwater system of Russian waterways amounts to several hundreds of million tons a year.

Recreational use of water reservoirs acquired wide circulation, especially for short-term (5–7 days) and week-end (1–2 days) recreation. Tens of millions of

Russian Water Reservoirs, Table 1 Russian largest water reservoirs

Title of reservoirs	River	Years of construction	Height of dam (m)	Total volume (km ³)	Active capacity (useful volume) (km ³)	Square (km ²)	Maximum depth (m)	Length (km)	Maximum width (km)	Amplitude change of level (m)	Coefficient of water change, numbers in during year	Numbers on map reservoirs of Soviet Union
Bratsk	Angara	1961–1967	190	169.3	48.2	5,470	150	1,020	25	10	0.5	22
Krasnoyarsk	Enisei	1967–1970	124	73.3	30.4	2,100	105	388	16	20	1.4	113
Zaysk	Zeya	1975	116	68.4	38.2	2,420	100	290	40	10	0.3	70
Ust-Ilimsk	Angara	1974–1977	110	59.4	2.8	1,922	97	300	7	2	1.7	236
Boguchansk	Angara	1980–2011	79	58.2	2.3	2,325	70	375	15	1	1.5	21
Kuibyshev	Volga	1955–1957	45	58.0	34.6	5,900	41	510	25	8	4.2	117
Vilujsk	Viluj	1965–1972	25	40.4	22.4	2,360	70	470	30	18	0.5	36
Volgograd	Volga	1958–1960	60	31.4	8.2	3,115	42	540	12	4	8.0	40
Rybinsk	Volga	1940–1949	35	25.4	16.7	4,550	31	250	56	5	1.4	189
Sayansk	Enisei	1980–1987	232	29.1	14.7	633	113	290	20	25	1.5	199
Tsimlyansk	Don	1952–1953	45	23.9	11.5	2,700	35	360	38	8	0.8	251
Bureisk	Bureya	1978–2005	140	20.9	10.7	740	120	234	5	12	0.7	24
Kolymsk	Kolyma	1983	117	14.6	6.5	440	100	150	6	15	0.5	109
Kureisk	Kureika	1979	85	13.4	10.1	750	70	110	12	12	0.4	118
Saratov	Volga	1967–1968	60	12.9	1.8	1,840	31	312	11	1	19	195
Kamsk	Kama	1954–1956	40	12.2	9.8	1,915	30	300	14	8	4.2	31
Votkinsk	Kama	1961–1964	45	9.4	3.7	1,120	28	365	10	4	5.7	42
Gorkovskii	Volga	1955–1957	37	8.8	2.8	1,590	22	430	16	3	6.0	53
Novosibirsk	Ob	1957–1959	35	8.8	4.4	1,070	25	200	18	5	5.9	158
Cheboksarsk	Volga	1982–1985	30	4.6	0.1	1,185	18	310	11	2	22	253

Russians visit water reservoirs for rest and sports. It is caused by the fact that many large cities of the country are located on the banks of water reservoirs, no less than 60 million people (about 45% of all the country's population) resides in the zone of 1-hour transport accessibility to water reservoirs.

Many water reservoirs of Russia have great value for domestic and industrial water supply of city agglomerations and large cities of Russia. It is caused by the fact that resources of underground waters having better quality of water in comparison with surface sources (rivers and lakes), as a rule, are not sufficient to meet the needs of the multi-million population of large cities and water-capacious branches of economy and industry (first of all, thermal and atomic engineering, metallurgical and chemical industry, agriculture). In Russia about 70% of the total water consumption volume is provided by surface sources. Dozens of large cities of Russia with the population more than 100 thousand people are supplied with water from water reservoirs. These are the cities located on the banks of water reservoirs of Kama, Volga, Don, Kuban, Ob, Angara, and Yenisey. Resources of non-regulated river runoff, as a rule, are not enough for the guaranteed water supply of the population, economy, and industry. The most typical example in this respect is the city of Moscow, the capital of Russia, which is located on the bank of the Moskva River, rather small in annual flow. The population, economy, and industry of the city had no serious prospects of development based on rather limited river and underground flow resources. In the end of the 1920s exploratory and design study was carried out for solving the problem of water supply of the Russian capital. The decision was made on building Ivankovsk water reservoir with seasonal regulation of the Upper Volga flow (total volume 1.12 km^3 , active capacity – 0.8 km^3 , area – 327 km^2 , length – 125 km), and on the construction of the Moscow Canal (the former name “the Moscow-Volga Canal”) 128 km in length for delivery of a part of the Volga flow to the Moskva River. These constructions were built in the shortest terms – in 5 years during 1932–1937. Until now the world hydraulic engineering practice considers this engineering project and its realization as one of the best in the world. In 1935, the population of Moscow did not exceed three million people; in 2010 it was officially estimated as nine million people, though many experts on town-planning consider, that the real current population is no less than 12 million people. Construction of Ivankovsk water reservoir and the Moscow Canal allowed to provide city development 75 years ahead. With construction of the Moscow Canal the city of Moscow became the port of five seas: Baltic, White, Azov, Black, and Caspian when there occurred an opportunity to use cargo vessels with displacement up to 5,000 register tons. Currently, Moscow is supplied with up to 2.5 km^3 of water per year using this channel, and the potential of this hydraulic engineering system is still far from being exhausted, and it maintains its importance in the twenty-first century. The system of

water reservoirs for water supply of Moscow further developed, in 1950s–1970s new water reservoirs on the Moskva River and its tributaries, as well as the new Vazuza hydraulic engineering system was built.

In 2011, the system of Moscow water supply includes 16 water reservoirs and 2 channels. This allowed to create one of the world's most reliable systems of a large megacity water supply. Reliability of Moscow water supply by different estimations amounts to 95–97%. It means that in 95–97 years of a 100, necessary amounts of water consumption and water disposal are provided; and if there is a shortage of water, industrial water-consumers are limited first; there were no such cases during the period from 1937 to 2011. All large water reservoirs of Russia carry out the functions of flood control, however, there are two main water reservoirs of flood control value. First of them, Zeysk reservoir was created in 1975 by Zeysk hydroelectric power station's dam, 116 m in height. Its total volume is 68.4 km^3 , active capacity – 38.2 km^3 , area – $2,420 \text{ km}^2$, length – 290 km , maximum width up to 40 km , and maximal depth about 100 m . Zeysk water reservoir has exclusively important flood control value. After its creation 75 thousand hectares of new fertile flood plane and terrace lands were developed, average annual damages from flooding in the Zeya River plain below the power plant dam decreased 3–4 times. The construction of large Bureysk water reservoir in the Far East of the country on Bureya River, tributary of the Amur River, is being completed. Flood control value of the water reservoir is even greater: 120–150 thousand hectares of agricultural lands will be protected from frequent flooding.

The use of water reservoirs for fishing industry in Russia is widely developed. According to official fishery statistics, the annual yield in various years was estimated in the range of 30–50 thousand tons per year. These seem underestimations since Russia has not managed yet to properly solve the problem of illegal fishing, the so-called poaching, which by virtue of different reasons increased greatly. By different expert estimations, it is considered that illegal fishing (without permits, licenses, and authorizations) can reach up to 50–100% of the total yield recorded by official statistics.

In creation of large water reservoirs in Russia the interests of a fishing industry were always considered and complex actions on the development of fishing were prepared. However, real fish yield in the absolute majority of water reservoirs turned out 3–15 times below the design levels for a number of reasons. Modern fish productivity of the most important water reservoirs of the country varies in a wide range from 1 kg per hectare (water reservoirs of Siberia) up to 40 kg per hectare (Tsimlyansk water reservoir on the river Don, the most productive in Russia). Three to ten kinds of fish are covered by fish industry in various water reservoirs of the country, and the industry volume of low value kinds reaches 60–80% of the total yield. One of the characteristics of Russia is that the so-called commercial fishery is carried out on water reservoirs of the country; in the majority of the developed

countries of the world commercial fishing is not carried out, but nonprofessional (recreational) fishing is widely developed.

Water reservoirs of Russia are widely used in the recreational purposes for mass leisure and sports of the population. The range of recreational activities is rather wide and totals several dozens of summer and winter activities. Recreation both in the recreational institutions (sanitariums, recreation centers, camps, leisure bases) and in the framework of riverside tourism and boating is popular. General recreational potential of Russia amounts to no less than one billion visits per year, especially considering weekend recreation of the country's urban population. Creation of many water reservoirs improved the recreation opportunities on reservoirs of this type, especially regarding the range of recreational activities. In many industrial regions of the country the water reservoirs are the main recreational objects. For example, the modern recreational potential of eight water reservoirs of the Volga cascade considering, first of all, ecological restrictions, amounts to 400 million visits per year. The situation in two of the Russian Federation constituent territories – in Moscow and the Moscow area – is indicative. These regions have very few large natural water objects (rivers and lakes) suitable for mass recreation of tens millions of people. The main objects of water recreation for inhabitants of Moscow and the Moscow region are the water reservoirs of the water supply system of the Russian capital of Russia. During the Soviet period recreational zones for the inhabitants of 23 municipal areas of Moscow were created that one could reach by railway, automobile, and water transportation.

The storage coefficient, that is, the ratio of active capacity of a water reservoir to the volume of long-term annual average runoff at the dam site varies for different water reservoirs of Russia within a wide range from 0.1 to 0.8. Water reservoirs carry out long-term, seasonal, weekly and daily regulation of river runoff.

Total water exchange coefficient in water reservoirs varies within wide range from 8 to 10 times annually (high-current water reservoirs) up to 1 time every 2–3 years (low-current water reservoirs). It is determined by many factors: parameters of a water reservoir, water inflow to the reservoir, and orientation of water resources' use.

Annual amplitude of water level fluctuations in water reservoirs of Russia is within the range from 1 m to 50 m.

The three-dimensional system of currents in large water reservoirs of Russia is rather complex, the main types are discharge currents, wind and wave currents, compensatory and drift currents. The speed of currents in the surface layer of water (0.5 m) decreases from 0.5 to 1.0 m/s in the upper part of water reservoirs to 0.10–0.20 m/s in the dam parts. The speed of bed currents is insignificant and amounts to several centimeters per second. Complex velocity profile of the currents is indicative, that is, the change of their vectors from the water surface to the bottom.

As a whole, water reservoirs of Russia can be viewed as transitional and accumulative hydro-ecological systems of transitional type water object between river and lake ecosystems. This determines the formation features of water quality, types, and ecological condition of bottom soil, orientation, and intensity of hydro-biological processes, structure, and variety of various types of water ecosystems within one large water reservoir.

There were long-standing discussions in Russia on whether the water reservoirs improve or worsen the quality of water, since the reduction of current speed and the decrease in turbulent exchange were traditionally considered as negative consequences of water quality formation. However, more experts lean toward complex evaluation of water reservoirs' positive influence on the quality of water. Such positive evaluation is based on the fact that the processes of intense wind-wave and convective mixing of water take place in water reservoirs; powerful water ecosystem produces plenty of oxygen, and, finally, the bottom soil accumulates large quantity of polluting and highly toxic substances. Back inflow of pollution from bottom soil to the water environment as a result of desorption processes is qualified as the process of secondary pollution. This problem was also actively discussed in Russia during last decades. Many large water reservoirs of federal and regional value in Russia have already been used for 50–60 years, and no secondary pollution has yet been noted.

On the most important water reservoirs of the country the monitoring of water quality by scores of hydrological, hydro-chemical, and hydro-biological parameters is carried out. For large water reservoirs strongly pronounced spatial-terminal heterogeneity of water quality parameters is characteristic, when concentration distinctions in various locations of a reservoir may reach 10–100 times. In Russia 1,750 parameters is a norm for economic-potable water supply. The most typical polluting substances in water reservoirs are easily oxidizable and hardly oxidizable organic compounds, petrochemicals, phenols, heavy metal compounds, and synthetic surface-active substances. Excess of the average annual content of the named compounds may reach 2–10 times in relation to maximum permissible concentration. There are areas of water with insignificant, average, and essential level of pollution in each of the large water reservoirs, especially during the winter period. As a rule, it is caused by the discharge of insufficiently purified service and industrial wastewater in the water reservoirs. For example, on the Volga water reservoirs there are more than five thousand of such drainage outlets.

There are about 15 types of bottom soil complexes in the water reservoirs of Russia, the speed of bottom sediments accumulation is usually insignificant and amounts to 0.5–4 mm per year. Strength of bottom sediments in dam areas can reach 1.5–2 m. Estimated sedimentation term in the majority of large water reservoirs amounts to several hundreds years.

High phytoplankton species diversity is characteristic for water reservoirs of Russia; up to 400 taxons are defined on a number of reservoirs. Intensive phytoplankton development, the so-called "blooming" of water, is usually connected with development of diatom and cyanobacteriae. In weak phytoplankton development its biomass amounts to 0.5–9.9, in intensive 10–99, and in hyperblooming more than 100 g/m³.

Average biomass of zoobenthos in 25 largest water reservoirs changes within a range from 1 to 42 g/m², and average biomass of zooplankton varies within range from 0.2 to 4.8 g/m³.

The degree of water reservoirs' weediness by the highest aquatic vegetation (deep, floating, and aero-aquatic) amounts to 0.4–30% of the water area.

In 1967, the world's largest river reservoir – Bratsk – was formed in Russia on the Angara River with capacity of 169.7 km³, area 5,467 km², maximal depth of 150 m, and length 1,020 km. Kuybyshevsk water reservoir on the Volga River built in 1957 is the largest reservoir in the Europe. Its volume is 57.3 km³, area 5,900 km², maximal depth – 41 m, and length – 510 km.

Creation of the Irkutsk (Baikal) water reservoir on the Angara River, the only river flowing out of the lake Baikal, led to increase of the lake level by 1.8 m. This caused extremely negative ecological consequences for the lake ecosystem regarding the activation of coast destruction processes and sharp reduction of population of the main industrial fish of Baikal – the well-known Arctic cisco. All these consequences during several dozens of years caused active indignation of ecologists and the public. Now, at the level of the Government of the Russian Federation the decision was made that the increase of Baikal water level more than 1 m is not allowed; special operating mode of the Angara-Yenisey hydroelectric power stations' cascade and water reservoirs is settled for this purpose. The most powerful hydroelectric power station of Russia is Sayano-Shushensk (6,400 mW) on the Yenisey river; the dam of 230 m in height forms Sayano-Shushensk water reservoir. Tragic events of August 2009 were related to this hydraulic engineering complex, when as a result of failure on the pressure head pipeline of one of the turbines, there was an instant water inflow in the machine hall, destruction of four turbines, and death of 72 people. It is the largest technogeneous accident related to hydraulic engineering constructions in Russia. No less than 5 years and costs of about five billion US Dollars are required for the station restoration.

Top ten of the world's most significant cascades of water reservoirs include the Volga-Kama (11 water reservoirs) and Angara-Yenisey (7 water reservoirs).

Creation of large water reservoirs in Russia essentially influenced practically all components of environment in the zone of influence of artificial reservoirs. It is related to flooding of a part of water-producing territories; flooding of coastal territories; climatic changes; formation of essentially different hydrological structure; new types of ecosystems; shore destruction; influence on flora and fauna; reorganization of industrial, economic, and transport infrastructure; and change of social and economic conditions of the population's life.

The area of flooding by construction of water reservoirs is estimated as 46,100 km² that is 0.27% of the total territory of Russia. Among the lands are woods, fields and meadows, and other lands, including settlement territories. No less than one million of people were moved from the zones of flooding and adverse influence on coastal territories.

Water reservoirs are natural-technical systems, and significant financial assets are necessary for the maintenance of their satisfactory engineering, technical, and ecological conditions. The main modern problem of the Russian water reservoirs is development and realization of the system complex of activities connected with the water reservoirs' operation mode, minimization of negative influences on environment, and improvement of social and economic conditions of living in the water reservoirs' influence zones. Water reservoirs of Russia are a part of the country's national riches. Prospects of creating new large hydro-units and water reservoirs in the nearest 25 years remain unclear due to high capital intensity of creating this type of objects and long terms of design and creation (usually no less than 15 years).

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S

SAKI, LAKE (CRIMEA, UKRAINE)

Rhodes W. Fairbridge (Deceased)

Description

Located at 45°07'N, 33°33' E near the west coast of the Crimean peninsula in Ukraine, Lake Saki is salty due to the high E:P ratio of the local climate.

It has become celebrated in paleoclimatology following a deep boring in the annually layered sediments, which average only 1–2 cm in thickness for each layer (varve). It may be noted that the Swedish term “varve” refers to an annually layered couplet of one dark-colored seasonal layer reflecting low precipitation and one light-colored layer representing the season with higher precipitation. In general, the rainfall intensity varies in phase with that of Central Asia but inversely with respect to Central and Western Europe.

A count of the varves by Schostakowitch in 1934 is reproduced in Lamb (1977, Figure 16.24, p. 408), together with a rainfall scale following a suggestion by Brooks (1949). The sequence goes back to 2294 B.C. Due to the thinness of the layers, some may, however, have been lost in the counting, but for long periods, this can be checked by repeat statistical sampling.

Time-series analyses have been undertaken by Xanthakis et al. (1995), using several different methods (MESA, or maximum entropy spectrum analysis; Blackmun–Tukey power spectrum analysis; PSA; Fourier FFT; autocorrelation). Interesting clusters of periodicities emerge over the entire series, notably 20–25, 44–46, 57–67, 120–130, and 200–250 years. Similar clustering is seen in long-term analysis of ¹⁴C flux levels in ten millennia of tree rings, and in magnetic and auroral records.

An earlier analysis of the Lake Saki varves based on less sophisticated methods by Dewey (1964) recognized a 17 1/3-year cycle, which periodicity he had also identified (with C. S. Jarvis) in flood stages of the River Nile during the first millennium. This periodicity appears to be a beat frequency developed by the two principal lunar tidal parameters, the 18.03-year “Saros” perigee-syzygy period and the 8.849-year apsides cycle, i.e., 17.3769 year.

Following the calculations by Brooks (1949, p.299), reproduced as a graph in Lamb (1977), the rainfall at Lake Saki around 2100–2300 B.C. fluctuated around 45–56 cm/year, but for a long interval, 2100 B.C. to A.D. 700, it hovered about 38–42 cm/year; it then rose to a moisture peak of 48 cm/year about A.D. 800, fell, and then rose again to 50 cm/year in 1,100–1,300, falling to 43–45 cm/year till the present. Elsewhere in Russia, Lamb noted a very marked increase in continentality, 1,300–1,450, but after that, it is interesting that Lake Saki displayed no evidence of the Little Ice Age. In general, Lamb notes the Lake Saki record oscillates in an inverse sense to that in western and northern Europe. Particularly, dry spells occurred in the 12th, 10th and 6th centuries B.C. and around A.D. 1250, just when western Europe was particularly wet (Lamb, 1977, p.408).

In view of the 21st century interest in extreme events (floods or droughts), the Lake Saki record provides specific data. In the 21st century B.C. when varve thickness average was 17 mm, in one uniquely distinctive year, 2177 B.C., it was 110 mm. Another, in 2150 B.C., was 230 mm, in 889 B.C. was 110 mm again, and in A.D. 805 was 220 mm. A hydrologic engineer would probably categorize these as “thousand-year floods.” Each was a “singularity” and *not* part of a trend.

In contrast, the dry spells or droughts tend to be drawn out, e.g., in 1873–1813 B.C., there were only 24 out of 60 years that produced a varve more than 10 mm thick. Immediately following the 889 B.C. flood, there followed,

in 888–870, 18 dry years with several varves as thin as 5 and 6 mm. Similar dry spells occurred in A.D. 1296–1292, citing some notable examples.

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Cross-references

[Lakes on Earth, Different Types](#)

[World Lake Database: International Lake Environment Committee Foundation \(ILEC\)](#)

SATELLITE DATA AND LAKES

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Description

The use of data obtained from sensors on satellite platforms implies that electromagnetic radiation emitted from objects on the ground is detected by a satellite sensor and analyzed in terms of different ground properties. Most sensors are passive, relying on emitted visible, near-, or thermal infrared radiation. Active sensors emit microwaves which are detected after backscattering on the ground. Different characteristics of satellites and sensors make them useful for different purposes – the revisit time for images of a certain area, the spatial resolution of images, the image area, the spectral resolution, the resolution of the detected radiation – and these properties have to be considered for possible lake applications. Most sensors are developed for land or ocean applications not considering possible, special demands for lakes, which means that the lake applications are somewhat restricted.

Main lake satellite data applications are related to:

- Surface area determination
- Water levels
- Water quality determination in terms of secchi depth, turbidity, chlorophyll contents

- Hydrodynamic processes (upwelling, mixing processes, thermal bars, etc.)
- Ice conditions

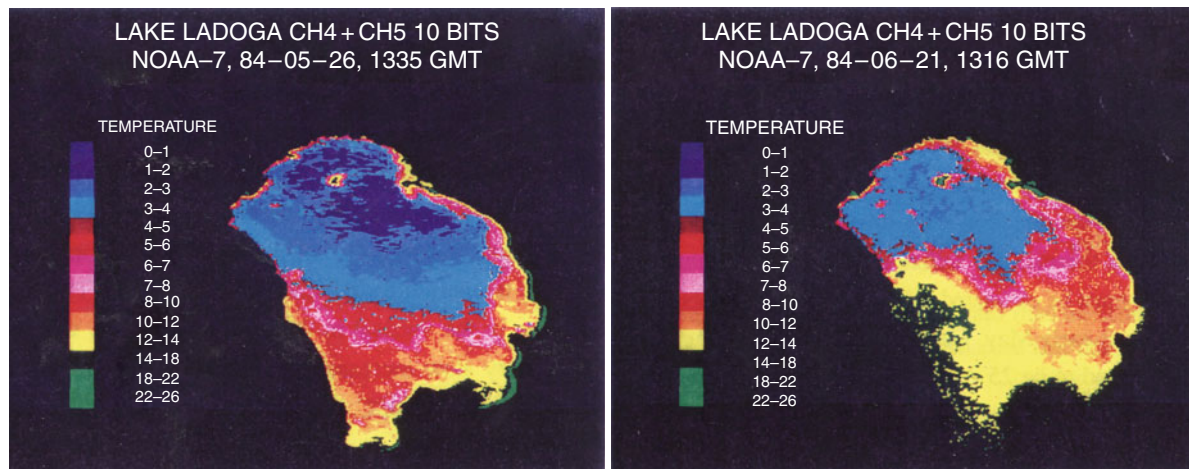
The application of water quality determination in terms of biological constituents such as algae (phytoplankton pigments, colored dissolved material [gelbstoff, etc.]) is of course important and of practical use. A problem is that water leaving radiance, related to water quality parameters, reaching the satellite sensor is commonly only about 10% and often less than 1% of the total sensor-detected energy. This means that reliable atmospheric correction is critical. The water quality signals from algae, for instance, can also be masked by high concentrations of gelbstoff, suspended inorganic particles, detrital material (case 2 waters) in contrast to open oceanic waters. Consequently, derived relations between satellite data and water quality parameters are site-specific. Reported applications mostly refer to large lakes. Generally speaking, the use of satellite data for monitoring lake properties and characteristics is less common than some other applications basically due to the fact that lakes often have a small surface area and that the optics of water and its constituents is complex.

Determination of surface area extent of (mostly large) lakes is an obvious and straightforward application utilizing a near-infrared spectral band as almost all of the incident light energy in this wave length band is absorbed at the water surface. Thus a lake surface is depicted as a distinct black area in optical satellite imagery. The shrinkage of Lake Aral and Lake Tchad has thus been studied using NOAA AVHRR (1.1-km spatial resolution), Landsat MSS (80-m) and TM (30-m) imagery, MODIS data (at least 250 m). Lake Poopo in Bolivia is an example of a small lake with a significantly changing surface area being studied with Landsat TM data with 30-m spatial resolution.

Active microwave satellites (synthetic-aperture radar, SAR) such as ERS-1 and ERS-2 with spatial resolutions of nominally 30 m can also be used for delineating lake water surfaces as a smooth water surface will not reflect any incident energy back to the satellite. SAR technology has the great advantage of not being hampered by clouds in contrast to optical imagery.

Studies on lake water levels have been reported for some large lakes such as Lake Kivu in Africa, using the radar altimeters on ERS-2 and ENVISAT with a footprint of a few kilometers.

Lake surface water temperatures (the uppermost few mm:s) have been determined using the two thermal infrared spectral bands of the NOAA AVHRR instrument (resolution 1.1 km) or the single thermal band of Landsat TM (resolution 120 m). The former utilizes the split-window technique offering a better temperature resolution (<1°C). Hydrodynamic phenomena can be studied indirectly using the surface temperatures. One example is given by Lake Ladoga where the existence and the propagation of the thermal bar (the 4°C isotherm) during the



Satellite Data and Lakes, Figure 1 Lake Ladoga. Sea surface temperature from May and June respectively. Boundary between light blue and dark red depicts the location of the thermal barrier (4°C) (After Malm 1994).

spring/early-summer heating of the lake was studied using NOAA AVHRR data, [Figure 1](#). Upwelling of cold water in a lake can also be studied, which has been reported from Lake Tanganyika in Africa, a phenomenon of practical interest for fisheries. A good correlation between pan evaporation and NOAA AVHRR surface water temperatures has been reported from Lake Okeechobee, Florida.

Derivation of different aspects on water quality from satellite data has been tried in many cases. The water depth visibility in terms of secchi depth has been determined in terms of Landsat 5 TM data using a combination of reflectance in band 1 (blue) and band 3 (red) respectively for a lake in Missouri, USA. An extensive study from Lake Erken, Sweden, surface area 24 km², described the use of Landsat TM data, band 1–4 algorithms, for deriving chl-a and SPM (total suspended particulate matter) contents. Construction of the algorithms using simultaneously obtained in situ data showed a good agreement between satellite and in situ data.

The more recent SeaWiFS sensor on the SeaStar satellite is primarily devoted to ocean applications with a spatial resolution of 1 km and with spectral bands devised for chl-a, gelbstoff, and suspended sediment mapping. Among reported lake tests are Lake Balaton, Hungary, Lake Constance, Switzerland, and Lake Erie, USA.

The SPOT 1, 2 satellites offer a very high spatial resolution, 20 m in multispectral mode and 10 m in panchromatic mode making delineation of small lakes possible. The three multispectral modes do not seem to be well adapted to lake studies, although efforts have been made to determine chl-a.

Ice freeze-up and ice breakup in a large number of Canadian lakes have been studied using NOAA/AVHRR-derived surface brightness temperature and SPOT/VGT near-infrared reflectance during a 10-year period. Comparison with in situ observation showed a good agreement.

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Cross-references

[Ladoga Lake and Onego Lake \(Lakes Ladozhskoye and Onezhskoye\)](#)
[Poopó Lake, Bolivia](#)

SEDIMENTATION PROCESSES IN LAKES

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Definition

- Allochthonous – From outside (often used to characterize materials transported from the drainage area to a lake).
- Anoxic sediment – Sediment devoid of free oxygen.
- Autochthonous – Originating from inside the lake.

Benthos – Organisms living in or on the river or lake bed.
Bioturbation – Mechanical mixing, for example of bottom sediments due to living organisms.

Catchment – The drainage basin which channels precipitation into a lake or single outflow.

Diffusion – The movement of atoms or molecules from a region of higher concentration of the diffusing species to regions of lower concentration.

Eutrophic – A lake rich in nutrients, usually resulting in high productivity.

Load – The flux (transport) from the catchment to the lake.

Partition coefficient K_d – The ratio between the amount of radionuclide attached to suspended matter per unit of mass and the amount of dissolved radionuclide per unit of volume of water.

Phytoplankton – Plant members of the plankton.

Primary productivity – The total production by photosynthetic and chemosynthetic activity of organic substances.

Resuspension – The remobilization of particles from the sediments of a water body by the action of water movement.

Sediment – The matter which has fallen to the bottom of a water body.

Sedimentation rate – The amount of matter deposited on the bottom of a water body per unit of surface and time.

Stratification – Division of lake water masses into horizontal layers with different physical and chemical properties.

Suspended matter – Matter suspended in lake and river waters.

Trophic level – The hierarchical level that an organism occupies in the food chain. The group of organisms that occupy the same level in the food chain.

contamination and relate natural fluxes to anthropogenic fluxes, and hence also to get realistic expectations of remedial measures. Sedimentological processes are fundamental parts of mass-balance models since they quantify internal transport processes in lakes, such as sedimentation, resuspension, and mixing. The approaches originally presented by Vollenweider (1968) have been followed by many others. The mass-balance approach to lake eutrophication has played a paramount role in lake management.

During the last 10 years, there has been a “revolution” in ecosystem modeling. The major reason for this development is, in fact, the Chernobyl accident (Håkanson, 2000). To follow the pulse of radiocesium through ecosystem pathways has meant that important fluxes and mechanisms have been revealed. It is important to stress that many of these structures and equations are valid not just for radiocesium in lakes, but for most types of contaminants, e.g., for metals, nutrients, and organics, in most types of aquatic environments.

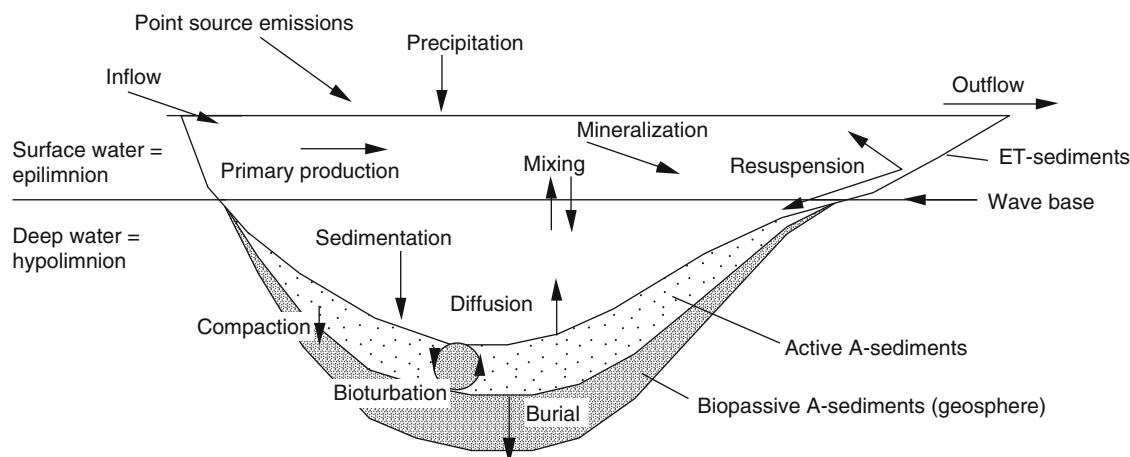
The predictive power of any mass-balance model for any given substance depends on the structure of the model and the numerical values and equations applied in the model. Generally, there are many ways to structure mass-balance models depending on the target y -variable to be predicted and the scale of the modeling, i.e., if calculations are done on a short-term basis (minutes-days) or long-term basis (years to centuries) or if site-typical information (using partial differential equations) or area-typical (whole lake) approaches are being used (and ordinary differential equations).

It is not possible to understand how lakes function without a basic knowledge of the transport processes that exist in all lakes and apply to all substances. Figure 1 gives a compilation of such processes. These processes have the same names for all lakes and for all substances:

- Sedimentation is the flux from water to sediments.
- Resuspension is the advective flux from sediments back to water.

Background of transport processes in lakes

Mass-balance models are since long fundamental tools in aquatic sciences to gain knowledge about processes and fluxes, in water management to identify sources of



Sedimentation Processes in Lakes, Figure 1 Illustration of general and fundamental transport processes to, within, and from lakes.

- Diffusion is the flux from sediments back to water triggered by concentration gradients.
- Mixing appears in stratified lakes and is the transport between deep-water areas and surface water areas.
- Mineralization is decomposition of organic particles by bacteria.
- Primary production is creation of living suspended particles from dead matter by sunlight.
- Burial is the transport of matter from the lake biosphere to the geosphere, often of matter from the technosphere.
- Outflow is the flux out of the lake of water of everything dissolved and suspended in the water.

Figure 2 exemplifies these sedimentological processes using data from Lake Geneva, Switzerland, which is large (503 km²) and deep (mean depth 72 m). Some typical characteristics related to sedimentation in lakes may be identified:

- Most fluxes appear with clear seasonal patterns.
- Mixing is a dominant flux, and upward mixing is smaller than downward mixing.
- Burial is smaller than sedimentation because there is substantial diffusion of phosphorus from the accumulation-area sediments, especially in the summer time when the lake has a relatively stable thermal stratification.
- The riverine inflow is driving the conditions (the trophic situation) in the lakes and this flux is significantly larger than the atmospheric precipitation of phosphorus.
- Resuspension is relatively small in this deep lake.
- There are two fluxes removing phosphorus from the lake, and the outflow is bigger than the burial.

The water depth that differentiates the surface water (epilimnetic) part of the lake from the deep water (hypolimnetic) (at 23 m in Lake Geneva) could, potentially, be related to (1) water temperature conditions and the thermocline, (2) vertical concentration gradients of dissolved or suspended particles, (3) wind/wave influences and wave characteristics, and (4) sedimentological conditions associated with resuspension and internal loading. There are several ways to characterize vertical heterogeneities in lakes. From a mass-balance perspective, it is necessary to work with clearly defined depths, volumes, and substance concentrations.

If one can find a relevant way of defining the water depth separating the surface water layer from the deep-water layer, this will also open possibilities to calculate outflow in a simple, operational, and mechanistic manner for water and everything dissolved and suspended in the water since the outflow is given by:

$$F_{\text{out}} = Q_{\text{out}} \cdot C_{\text{SW}} \quad (1)$$

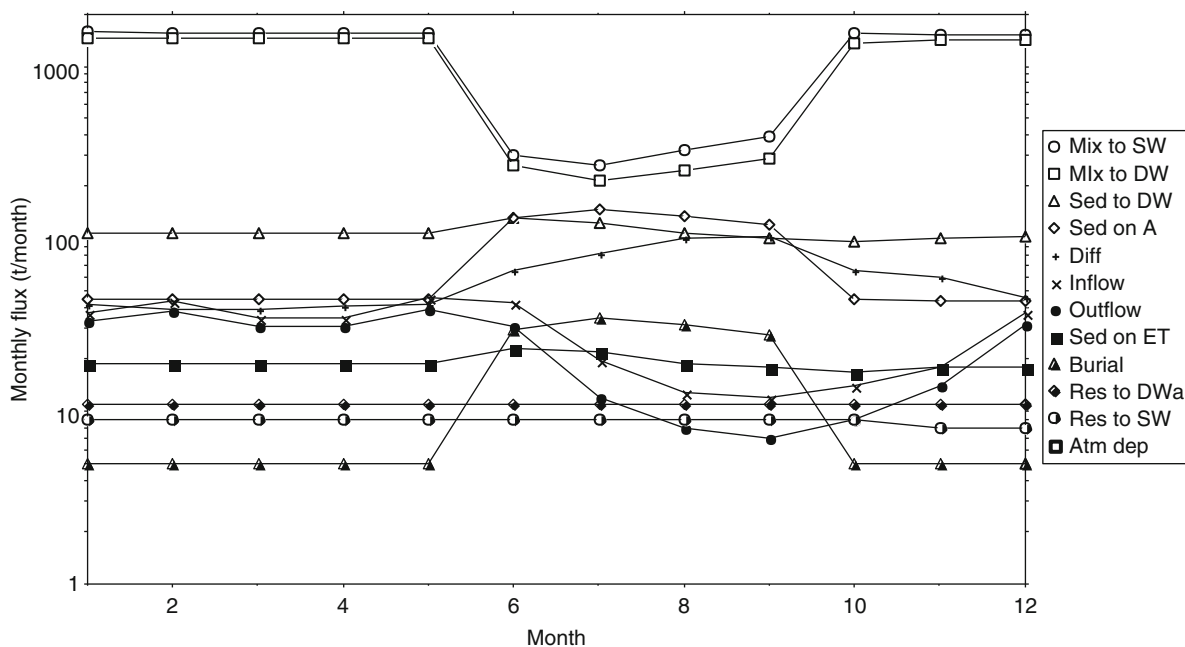
F_{out} = outflow of the given substance in dissolved or particulate form in g X per week or month.

Q_{out} = water transport out of the lake in m³ per week or month.

C_{SW} = the concentration of the substance in the surface water in g X/m³.

The concentration of the substance in the surface water, C_{SW} , is defined from the following ratio:

$$C_{\text{SW}} = M_{\text{SW}}/V_{\text{SW}} \quad (2)$$



Sedimentation Processes in Lakes, Figure 2 Monthly fluxes of phosphorus in Lake Geneva, Switzerland (using the LakeMab-model; see Håkanson and Bryhn, 2008).

M_{SW} = the mass or amount of the substance X in the surface water compartment (g X).

V_{SW} = the volume of the surface water compartment (m^3).

The volume of the surface water compartment, in turn, is a function of the lake area, the depth separating surface water from deep water, and the form of the lake (as given by the hypsographic curve).

A proper definition of the water depth separating the surface water layer and the deep-water layer is also important in quantifying sedimentation, because sedimentation of particulate matter from the surface water to the deep water, and from the deep water to the lake bottom, is related to the settling velocity of the suspended particles (v in m/week or month) and the mean depth of the two respective compartments, D_{SW} and D_{DW} . Basically, sedimentation (F_{SWDW} , i.e., sedimentation from surface water to deep water) is given by:

$$F_{SWDW} = M_{SW} \cdot (v/D_{SW}) \cdot PF \quad (3)$$

where PF is the particulate fraction, the only fraction subject to gravitational sedimentation.

Defining the surface water and the deep water layers also means that one can define upward and downward mixing.

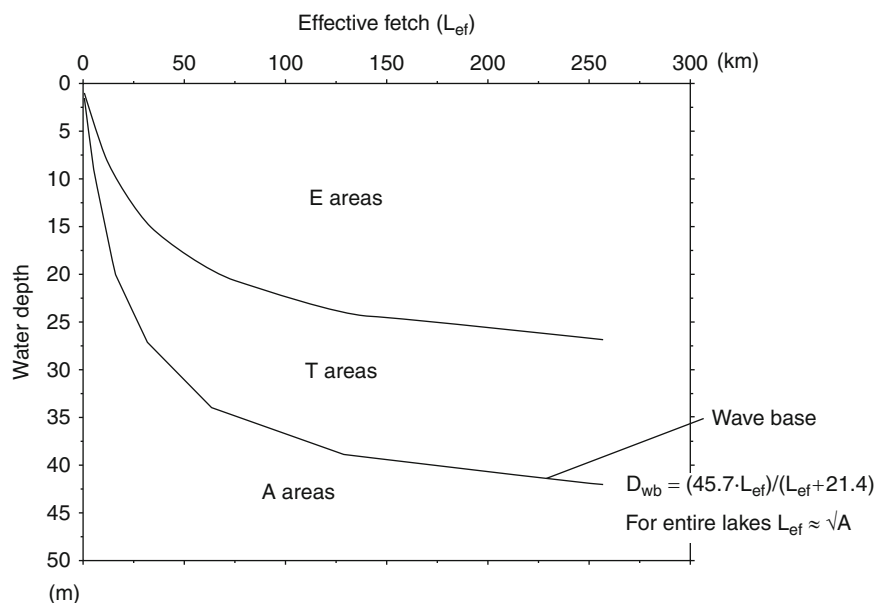
This section will also present an approach to calculate those areas of the lake bed where resuspension is likely to occur (the areas of fine sediment erosion and transport, the ET areas; see Figure 3). The depth separating areas where resuspension is likely to prevail from the areas with continuous sedimentation of fine material is called the wave base.

The thermocline

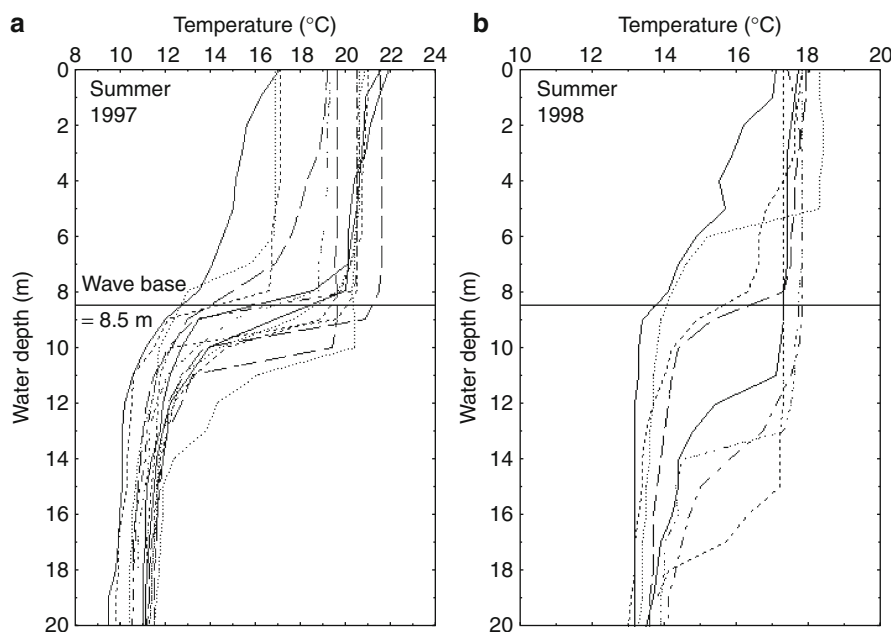
To use the thermocline as the key criteria to differentiate between the surface water and the deep water is certainly the most classical approach (Wetzel, 2001). But that does not necessarily imply that it is operational in contexts of mass-balance calculations. This is demonstrated in Figure 4 using data from Lake Erken, Sweden. For single sites after longer periods without strong winds in the summer, one can certainly see clear thermoclines. However, for many sites over longer periods of time (weeks and months), it is generally very difficult to define the critical water depth requested in mass-balance calculations – any water depth between 0.1 and 18 m in Lake Erken, which has a maximum depth of 23 m, could be used! The data shown in Figure 4 for Lake Erken are included here to emphasize that for this lake, and for lakes in general, the thermocline may be a poor alternative for the water depth separating areas where resuspension is likely to occur from the deeper accumulation areas. Water temperatures do not provide consistent information to define the boundary between surface water and deep water.

Suspended particulate matter: a definition

The total amount of a substance or a group of substances in the water is often separated into a particulate phase, the only phase subject to gravitational sedimentation, and a dissolved phase, generally the most important phase for direct biouptake. Operationally, the limit between the particulate phase and the dissolved phase is generally determined by means of filtration using a pore size of



Sedimentation Processes in Lakes, Figure 3 The ETA diagram (Erosion-Transportation-Accumulation; for more information, see Håkanson and Jansson, 1983) illustrating the relationship between effective fetch, water depth and bottom dynamic conditions. The wave base (D_{wb}) can be used as a general criterion to differentiate between surface water and deep water in lakes.



Sedimentation Processes in Lakes, Figure 4 Temperature data from Lake Erken, Sweden (unpublished data for the summers of 1997 and 1998 from ongoing monitoring) and illustration of the wave base in this lake. Each line represents the temperature profile at the monitoring station at a given sampling occasion. (From Håkanson et al., 2004.)

0.45 μm . Evidently, this is an operational approach and many colloidal particles will pass such filters and are, hence, operationally included in the dissolved fraction, although they are not truly dissolved in a chemical or biological sense. Suspended particulate matter (SPM) as determined in this way by filtration, drying, and weighing, is sometimes also referred to as SSC, the suspended sediment concentration. Filtration is often a justifiable method from sedimentological, ecological, and mass-balance modeling perspectives.

Figure 5 classifies SPM according to origin. Many factors are known to influence SPM in aquatic systems. The most important factors are:

1. Autochthonous production (i.e., the amount of plankton, feces, etc., in the water – more plankton, etc., means a higher SPM).
2. Allochthonous materials, such as the amount of colored matter (e.g., humic and fulvic substances).
3. The amount of resuspended material.

These three factors are not independent: High sedimentation leads to high amounts of resuspendable materials; high resuspension leads to high internal loading of nutrients and increased production; a high amount of colored substances means a smaller photic zone and a lower production; a high input of colored substances and a high production would mean a high sedimentation, etc.

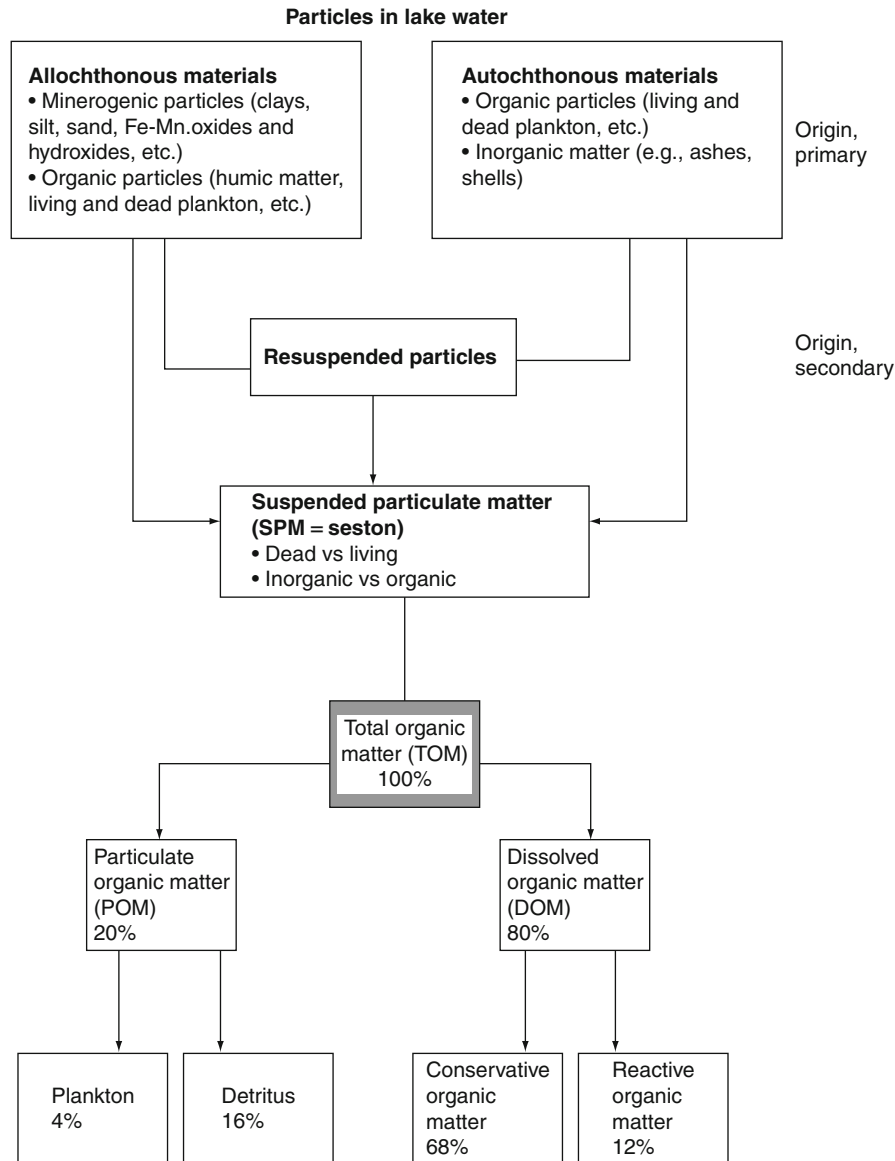
SPM is generally a complex mix of substances of different origins with different properties (size, form, density, specific surface area, capacity to bind pollutants,

etc.). SPM may be divided into an organic fraction (POM) or an inorganic one (PIM, particulate inorganic materials). Total organic matter (TOM) is generally divided into particulate (POM) and dissolved (DOM) fractions. Normally, POM is about 20% of TOM, but this certainly varies among and within systems. Normally, about 4% of POM is living matter and the rest is dead organic matter (detritus). About 80% of TOM is generally in the dissolved phase, and of this about 70% is conservative in the sense that it does not change due to chemical and biological reactions in the water mass.

Sedimentological processes

From this background, the aim of the following section is to define and explain some fundamental sedimentological processes starting with sedimentation.

In quantifying lake sedimentological processes, lakes are often divided into four zones: Surface water, deep water, ET areas (areas where processes of fine sediment erosion and transport dominate the bottom dynamic conditions), and accumulation areas (A areas). The following abbreviations for such fluxes are generally: F for fluxes (g/month), C for concentrations (g/m^3), R for rates ($1/\text{month}$), and M for masses (= amounts in g). Fluxes from one compartment to another are denoted, for example, F_{SWDW} for sedimentation from surface water (SW) to deep water (DW). The resuspended matter can be transported either back to the surface water (F_{ETSW}) or to the deep water (F_{ETDW}). How much will go in either



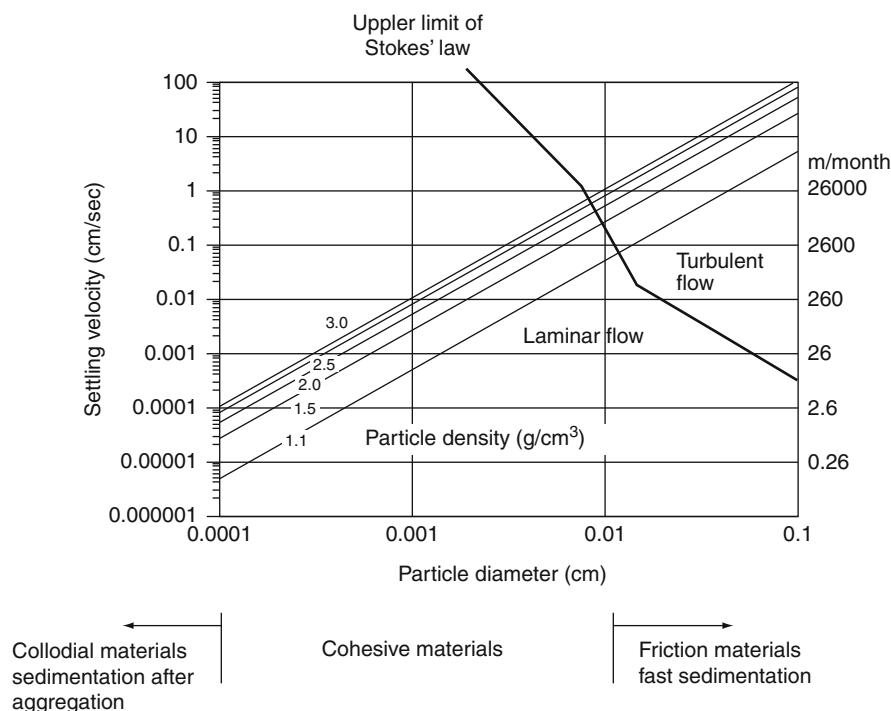
Sedimentation Processes in Lakes, Figure 5 Classification of particles in water (see Ostapenia, 1985).

direction is regulated by a distribution coefficient (DC) calculated from the form of the lake.

Sedimentation of suspended particles depends on:

1. A default settling velocity, v_{def} which is substance specific and related to the type of carrier particle. Examples are 12 m/year for illite clays, the carrier particles for radiocesium (Håkanson, 2000) or 72 m/year for planktonic materials (Håkanson and Boulion, 2002). The v value is changed into a rate (1/month) by division with the mean depth for the surface water areas (D_{SW}) for sedimentation on the ET areas above the wave base and by the mean depth of the deep-water areas (D_{DW}) for sedimentation in deep-water areas (the A areas) below the wave base.
2. The concentration of suspended particulate matter (SPM in mg/l) will influence the settling velocity. The greater the aggregation of suspended particles, the bigger the flocs and the faster the settling velocity.
3. The amount of resuspended matter will settle faster than the primary materials. The resuspended particles have already been aggregated and they have also generally been influenced by benthic activities, which will create a “gluing effect.”

The wave base is often determined from the ETA diagram (Erosion-Transportation-Accumulation). This approach (Figure 3) focuses on the behavior of the cohesive fine materials settling according to Stokes' law (see Eq. 4 and Figure 6). The grain size and/or the



Sedimentation Processes in Lakes, Figure 6 The relationship between the settling velocity (v_s) of spherical particles) in water, particle diameter, and particle density (at 20°C) as given by Stokes' law.

composition of the material are often used as criteria to distinguish different sediment types. One can also differentiate between different sediment types by means of functional criteria (like erosion, transportation, and accumulation) of coarse sediments (friction material) or fine sediments (cohesive material). In geoeological contexts, it is common to focus on the finer materials most easily set in motion/resuspension and having the highest capacity to bind pollutants. In defining the bottom dynamic conditions (erosion, transportation, and accumulation), this work uses the following definitions:

- Areas of erosion (E) prevail where there is no apparent deposition of fine materials but rather a removal of such materials, e.g., in shallow areas or on slopes; E-areas are generally hard and consist of sand, gravel, consolidated clays, and/or rocks.
- Areas of transportation (T) prevail where fine materials are deposited periodically (areas of mixed sediments). This bottom type generally dominates where wind/wave action regulates the bottom dynamic conditions (see Figure 3). It is sometimes difficult in practice to separate areas of erosion from areas of transportation.
- Areas of accumulation (A) prevail where the fine materials are deposited continuously (soft bottom areas). These are the areas (the "end stations") where high concentrations of pollutants may appear (see Table 1).

The generally hard or sandy sediments within the areas of erosion (E) often have a low water content, low organic content, and low concentrations of nutrients and pollutants (see Table 1). The conditions within the T-areas are, for natural reasons, variable, especially for the most mobile substances, like phosphorus, manganese, and iron, which react rapidly to alterations in the chemical "climate" (given by the redox potential) of the sediments. Fine materials may be deposited for long periods during stagnant weather conditions. In connection with a storm or a mass movement on a slope, this material may be resuspended and transported up and away, generally in the direction toward the A areas in the deeper parts, where continuous deposition occurs. Thus, resuspension is a most natural phenomenon on T areas.

It should also be stressed that fine materials are rarely deposited as a result of simple vertical settling in natural aquatic environments. The horizontal velocity is generally at least 10 times larger, sometimes up to 10,000 times larger, than the vertical component for fine materials or flocs that settle according to Stokes' law.

The particles settling on accumulation areas (A areas) are, by definition, not further resuspended by physical forces. However, such particles can be eaten by zoobenthos, and zoobenthos by fish, so these particles can be transported up to the lake water again in this manner. They can also be transported by migrating zooplankton between the sediments and the water column. These

Sedimentation Processes in Lakes, Table 1 The relationship between bottom dynamic conditions (erosion, transportation and accumulation), and the physical and chemical character of the surficial sediments of Lake Vänern, Sweden. Mean values (MV) and standard deviations (SD) in brackets (From Håkanson and Jansson, 1983)

	Erosion <i>n</i> = 14	Transportation <i>n</i> = 16	Accumulation <i>n</i> = 84
Physical parameters			
Water depth (m)	14.9 (9.7)	22.6 (10.3)	42.8 (22.5)
Water content (% ww)	40.3 (14.5)	64.0 (17.9)	84.0 (10.9)
Bulk density (g/cm ³)	1.58 (0.24)	1.27 (0.19)	1.10 (0.08)
Organic content (loss on ignition, % dw)	1.5 (0.8)	4.5 (2.3)	9.7 (5.3)
Nutrients (mg/g dw)			
Nitrogen	0.78 (0.33)	1.14 (0.46)	2.7 (0.53)
Chemically mobile elements			
Phosphorus	0.30 (0.50)	1.07 (0.80)	1.5 (1.0)
Metals (contaminating in this lake; µg/g dw)			
Mercury	0.026 (0.028)	0.27 (0.48)	1.34 (2.13)
Cadmium	<<1 (0.50)	0.7 (0.5)	1.4 (0.8)
Copper	13 (9)	26 (10)	30 (7)
Lead	34 (17)	64 (36)	104 (34)
Zinc	110 (63)	240 (125)	430 (210)
Nickel	22 (9)	31 (12)	28 (7)
Metals (non-contaminating in this lake; µg/g dw)			
Silver	<1	<1	<1
Boron	<20	<20	<20
Beryllium	<1	<1	<1
Bismuth	<10	<10	<10
Chromium	<50	<50	<50
Molybdenum	<20	<20	<20
Tin	<20	<20	<20
Vanadium	110 (46)	150 (47)	150 (29)

n = number of samples

particles will also be mineralized and decomposed by sediment-living bacteria and then the newly formed dissolved phase can migrate up to the lake water phase by diffusive processes. Bioturbation, i.e., the mechanical mixing of sediments by sediment-living organisms, can also contribute to the transport of settled particles both back to the water and downward to the biologically passive sediments.

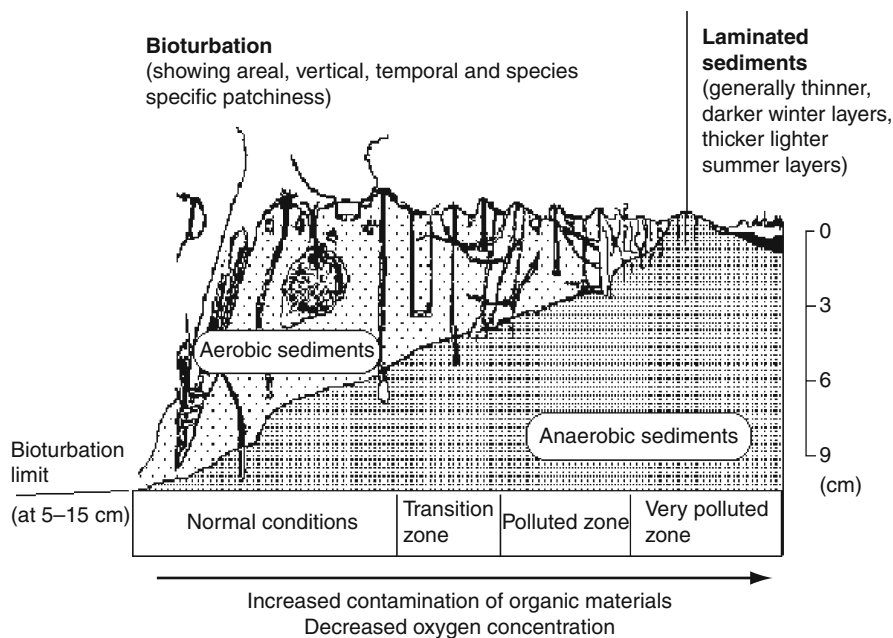
Generally, various types of zoobenthos live in sediments down to about 5–15 cm sediment depth (see Figure 7). This upper part of the sediment column is biologically active in the sense that the bottom fauna can influence the physical, chemical, and biological conditions of the sediments and cause bioturbation. However, the larger animals (macro- and meiofauna) generally die if the oxygen concentration becomes lower than about 2 mg/l. This will stop the bioturbation and laminated (layered and unmixed) sediments may appear. The continuous sedimentation will cause the sediment layer to grow upward so that the bioturbation limit, i.e., the limit between the upper biological layer and the lower biopassive (or geological) layer moves upward.

Many polluting substances have a considerable particle affinity. This means that the behavior of all substances with a particular phase in aquatic systems is influenced

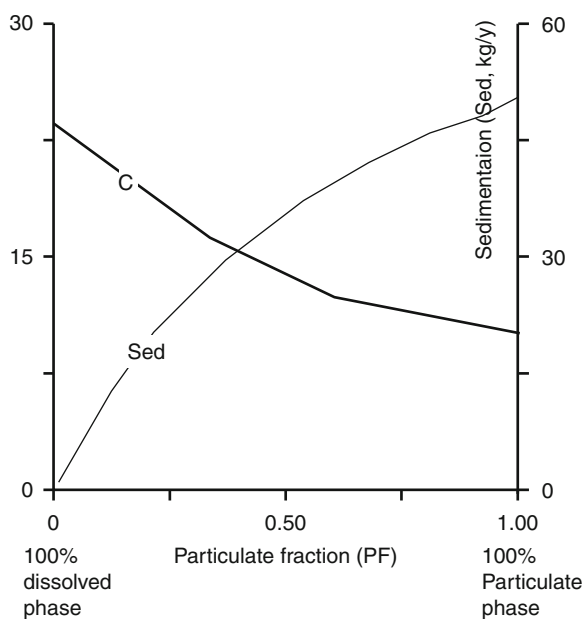
by SPM. In addition, the retention of a given substance in a system will be governed by the turnover time of the water, i.e., the longer the water turnover time, the larger the proportion of the initial load retained within the system.

A very important part of most mass-balance models for chemical substances is the distribution coefficient. The distribution coefficient is also often called the partition or partitioning coefficient and gives the particulate fraction (PF) or the dissolved fraction (DF = 1–PF). The organic particulate fraction and the colloidal fraction may be subject to mineralization by bacterioplankton. Figure 8 illustrates the very important role that the PF-value plays for the concentration of phosphorus in water and for sedimentation of phosphorus. It is evident that the PF-value influences the concentration in lake water: The higher the particulate fraction, the less in dissolved form, the higher the sedimentation, and the lower the concentration in water, and vice versa. This is a general principle valid for all substances. PF = 1 for SPM.

Geochemically, fine, cohesive materials behave differently compared to coarse (friction) materials. From the basic Stokes' equation for settling particles (Eq. 4), as well as for convenience, the limit between coarse and fine materials can be set at a particle size of medium silt.



Sedimentation Processes in Lakes, Figure 7 Bioturbation and laminated sediments. Under aerobic (= oxic) conditions zoobenthos may create a biological mixing of sediments down to about 15 cm sediment depth (the bioturbation limit). If the deposition of organic materials increase and hence also the oxygen consumption from bacterial degradation of organic materials, the oxygen concentration may reach the critical limit of 2 mg/l, when zoobenthos die, bioturbation ceases, and laminated sediments appear (Figure modified from Pearson and Rosenberg, 1976).



Sedimentation Processes in Lakes, Figure 8 Illustration of the important role of the particulate fraction of phosphorus in mass-balance calculations (annual simulations for a lake with an area = 1 km²; mean depth = 10 m; catchment area = 10 km²; mean annual precipitation = 650 mm/year; mean tributary concentration = 26 µg/l of total phosphorus; and a settling velocity of 5 m/year for the particulate fraction).

Stokes' law expresses the settling velocity (v) as:

$$v = \frac{(d_w - d_p \cdot g \cdot d^2)}{(18 \cdot AV \cdot FR)} \quad (4)$$

v = the settling velocity (usually in cm/s)
 d_p = the particle density (usually in g dw/cm³; g dw = gram dry weight)
 d_w = the density of the lake water (often set to 1 g ww/cm³; g ww = gram wet weight)
 g = the acceleration due to gravity (980.6 cm/s²)
 d = the particle diameter (in cm)
 AV = the coefficient of absolute viscosity (obtained from standard tables; 0.01 poise at 20 °C)
 FR = the coefficient of form resistance (set to 1 for spheres; Hutchinson, 1967)

Stokes' law (Stokes, 1851) is depicted in Figure 6. The behavior of materials that follow Stokes' law (i.e., particles with a diameter between about 0.01 and 0.0001 cm) differs from the coarser friction material and the still finer material. The sedimentological behavior of the friction material is closely linked to the grain size of the individual particles; the sedimentological behavior of the very fine materials is governed by Brownian motion. These latter particles are so small that they will not settle individually, but will do so if they form larger flocs or aggregates which are dense enough to settle according to Stokes' law. The cohesive materials that follow Stokes' law are very important,

since they have a great affinity for pollutants. This group includes many types of detritus, humic substances, and plankton. All play significant roles in aquatic systems.

The settling velocity (v) of a given particle, aggregate, or particulate pollutant, and its distribution in an aquatic system, depends on the density, size, and form of the particle (and on the hydrodynamics of the flow of water in the system). If the particle density, d_p , is close to 1, if the form factor, FR, is large, and if the diameter, d , is small, the settling velocity, v , may be very small. If v is close to 0, the particle or aggregate is conservative in the sense that it may not be deposited in the system. In many lakes, Cl and alkalinity are often conservative substances, and color, organic matter, total-P, Si, particulate-P, and SPM are more reactive.

Summary/conclusions

Lake sediments are an important, integral part of the lake ecosystem. They reflect changes in land-use and lake characteristics and are often regarded as an historical archive. They also affect the present structure and function of lake ecosystems. Suspended particulate matter (SPM) in lakes mainly emanate from tributaries (allochthonous matter), from living and dead matter produced in the lake (autochthonous matter), or from resuspended materials. SPM regulates the transport of all types of water pollutants in dissolved and particulate phases; it regulates water clarity and the depth of the photic zone, and hence also primary and secondary production; it regulates bacterioplankton production and biomass, and hence also mineralization, oxygen consumption, and oxygen concentrations; and it regulates sedimentation, and hence also the use of sediments as an historical archive, e.g., of water pollutants. These matters are discussed in this chapter. The aim of the information given is to structure existing knowledge on the factors regulating variations among and within aquatic systems of suspended particulate matter in a rational manner. This knowledge is fundamental for an understanding of the function and structure of aquatic systems.

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Cross-references

[Reservoir Sedimentation](#)
[Stratification in Lakes](#)
[Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes](#)
[Wind Waves](#)

SEDIMENTS, FLUSHING FROM RESERVOIRS

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Introduction

There are around 40,000 large reservoirs worldwide used for water supply, power generation, flood control, etc. Between a half and 1% of the total storage volume is lost annually as a result of sedimentation, and 300–400 new dams need to be constructed annually just to maintain current total storage. However, increasing populations and increasing consumption per capita mean that the demand for storage is rising inexorably despite the increasing use of alternative sources and the more efficient use of water. The introduction of flushing facilities in some old dams, where appropriate, and in the design of new dams could help to minimize this need for additional storage.

The benefits attributable to dams and reservoirs, most of which have been built since 1950, are considerable, and stored water in reservoirs has improved the quality of life worldwide. These benefits can be classified under three main headings:

Irrigation: About 20% of cultivated land worldwide is irrigated, some 300 million hectares. This irrigated land produces about 33% of the worldwide food supply. Irrigation accounts for about 75% of the world water consumption, far outweighing the domestic and industrial consumption of water.

Hydropower: About 20% of the worldwide generation of electricity is attributable to hydroelectric schemes. This equates to about 7% of worldwide energy usage.

Flood control and storage: Many dams have been built with flood control and storage as the main motivator,

e.g., the Hoover dam, the Tennessee Valley dams, and some of the more recent dams in China.

In many areas of the world, the life span of reservoirs is determined by the rate of sedimentation which gradually reduces storage capacity and eventually destroys the ability to provide water and power. Many major reservoirs are approaching this stage in their life.

One way of preserving reservoir storage is to flush sediments through purpose built outlet works within the dam. This technique can be applied to existing dams (with adaptation of the engineering works) and to new dams. However, the technique is only effective under certain favorable conditions and is not universally applicable. The alternative is to build more dams to replace the depleting storage of the existing stock. However, there are fewer and fewer good dam sites available, and new dams can have serious environmental and social consequences.

A recent study carried out by HR Wallingford (White et al., 1999 and White, 2001) has evaluated where and when the flushing of sediment may be an appropriate method of sustaining reservoir storage. The study included the following aspects:

- An assessment of the scale of the problem of reservoir sedimentation
- An estimation of the volume of storage that is likely to be required to meet continuing demand
- A review of the current state of knowledge of mechanism of sediment flushing from reservoirs
- A review of the worldwide experience of sediment flushing from reservoirs
- Identification, in general terms, of the areas of the world where flushing is likely to be most useful

This contribution summarizes the lessons learned in the HR study without giving all the supporting evidence. Readers are referred to the HR report and the Thomas Telford book for full coverage of the work.

There is a distinction between sediment flushing and sediment sluicing. Sediment flushing is concerned with the removal of sediments which have settled in the reservoir at a previous time, whereas sediment sluicing is concerned with passing sediments straight through the reservoir during times of flood. The distinction is sometimes difficult to make. But, generally, sediment flushing is used to remove sediments up to and including sands and gravels, whereas sediment sluicing removes only the finer fractions. It is the sands and gravels which determine the ultimate sustainable volume of any reservoir, and hence, the following sections predominantly relate to *sediment flushing* (Figure 1).

Review of sedimentation in reservoirs

World storage: The best estimate of world storage in reservoirs (excluding natural lakes used as storage for power and irrigation) is approx. 7 000 km³.



Sediments, Flushing from Reservoirs, Figure 1 Reservoir sedimentation, Zimbabwe.

Distribution of storage: The worldwide distribution of existing storage and storage under construction as determined from the ICOLD Register (1998) is shown below:

Region	Number of dams	Gross storage (km ³)	Fraction of world total	Average size of reservoir (M.m ³)
N. America	7,205	1,845	29%	256
S. America	1,498	1,039	16%	694
N. Europe	2,277	938	15%	412
S. Europe	3,220	145	2%	45
Sub Saharan Africa	966	575	9%	595
North Africa	280	188	3%	652
China	1,851	649	10%	351
S. Asia	4,131	319	5%	77
C. Asia	44	148	2%	3,364
Southeast Asia	277	117	2%	424
Pacific Rim	2,778	277	4%	100
Mid. East	895	224	3%	250
World total	25,422	6,464	100%	254

The Americas together with Northern Europe and mainland China account for 70% of the existing world stock of reservoir storage.

Demand for more storage: The world population in 1999 is estimated to be 6,000 million, growing at an annual rate of 1.5%. This rate of growth is forecast to decline in the coming decades giving an estimated population in 2050 of 10,000 million.

Water demand is expected to continue to grow at a faster rate than predicted by population growth alone. Much of this demand will be satisfied by increased surface and groundwater abstraction and water reuse, and no direct linkage between overall demand and water storage can be assumed.

From the rates of growth for population, water consumption, estimated irrigation, and hydropower requirements, the demand for new storage is estimated as:

Region	Demand for new storage (km ³)		
	2000–2010	2010–2020	2020–2030
Europe	50	50	55
South and Central America	465	495	425
Africa	165	205	250
Asia and Oceania	315	280	215
Total	995	1030	945

Loss of storage: The rate of loss of storage for a given reservoir is dependent on the sediment yield from the catchment which, in turn, is dependent upon the rate of erosion and the transport, by water, of the sediment within the catchment. In regions where the catchments have remained stable, e.g., Northern Europe and North America, the rate of loss of storage is sensibly constant. In regions where deforestation has occurred, the rate of catchment erosion and consequently the rate of loss of storage increase.

The highest rates, in percentage terms, of loss of storage are found in the smallest reservoirs and the lowest rates in the largest. Of the 1,105 reservoirs documented, 730 have a storage volume of less than 1,233 million cubic meters and an average rate of loss of storage in excess of 1% per annum. At the other extreme, 23 of the reservoirs have a storage volume in excess of 1,233 million cubic meters and an average rate of loss of storage of 0.16% per annum. The worldwide average for the loss of storage due to sedimentation is between 0.5% and 1.0% per annum – a very significant amount.

Factors which influence viability and efficiency of sediment flushing

For effective flushing the following factors need to be considered and satisfied:

Hydraulic conditions required for efficient flushing: Riverine conditions must be created in the reservoir for

a significant length of time. The reservoir level must be held low throughout the flushing period, possibly with minor fluctuations in level to activate sediment movement. To achieve this:

- The hydraulic capacity of the bypass must be sufficient to maintain the reservoir at a constant level during the flushing period.
- Flushing discharges of at least twice the mean annual flow are required.
- Flushing volumes of at least 10% of the mean annual runoff should be anticipated.

Quantity of water available for flushing: There must be enough water available to transport the required volume of sediment. This has the following implications:

- Reservoirs where the annual runoff is large compared with the volume of the reservoir are best suited for sediment flushing.
- A regular annual cycle of flows and a defined flood season provide optimum conditions for sediment flushing. This favors sites in monsoon areas and sites where flood flows are generated by annual snowmelt in the spring and summer months.
- A balance must be achievable between the significant quantities of water required for sediment flushing and water required to satisfy demands at other times of the year – for irrigation and hydropower, for example.

Mobility of reservoir sediments: Sediment sizes are an important factor in determining whether the quantity of water available for flushing will be adequate to remove the desired quantity of sediment from the reservoir.

- Deposited coarse sediments are more difficult to remove than fine sediments. These sediments progress from the upstream end of the reservoir, and the toe of the foreset slope reaches the dam well into the life of the reservoir. The sustainable volume achievable by sediment flushing depends on the nature of the deposited sediments and other factors.
- The sediment sizes in transport in rivers entering a reservoir can be of paramount importance in determining the success of flushing. From the point of view of achieving a sediment balance, a large factor is desirable between the sediment sizes being transported as suspended bed material load in the rivers entering the reservoir and the sizes found in the river bed material. Such conditions are typical for gravel rivers with a widely varying bed material composition. In large rivers, this situation is found where the longitudinal bed gradient is between, say, 0.002 and 0.001. In smaller rivers, the equivalent range may be 0.005–0.002.
- From the point of view of sediment size alone, delta deposits of fine sand and coarse silt are the most likely to produce success in flushing a reservoir. Coarser

material may inhibit a sediment balance, and finer material will deposit in the body of the reservoir outside any incised channel and so will not be available for reworking during flushing.

Site specific factors: The most suitable conditions for flushing are to be found in reservoirs which approximate in shape to the incised channel which develops during flushing. Long, relatively narrow reservoirs are better suited to flushing than short, wide, shallow reservoirs.

Worldwide experience of sediment flushing

The HR study looked at 50 reservoirs which are being or have been flushed. In some cases the flushing was successful; in others there was little or no success. The main findings from this worldwide review, some of which confirm directly the semi-independent analysis of those hydraulic factors which favor sediment flushing, are:

- *The hydrology and sedimentology of the catchment:* The hydrology and sedimentology of the catchment need to be fully understood in the planning of flushing facilities for new or existing reservoirs and to provide the background for analyses of past sedimentation and flushing performance.
- *The storage capacity of the reservoir:* Successful hydraulic flushing is more likely to be practicable in reservoirs which are hydrologically small, with a storage capacity less than 30% of the mean annual inflow. The smaller the reservoir, the greater the chance of it being successfully flushed and the larger the likely residual storage capacity.
- *The sediment deposition potential:* Flushing is vital for the preservation of long-term storage in reservoirs where the sediment deposition potential is greater than 1–2% of the original capacity.
- *The shape of the reservoir basin:* Worldwide experience confirms that the shape of the reservoir basin can have a large impact on the practicability of effective flushing and the residual storage capacity. Narrow steep-sided reservoirs in valleys with a steep longitudinal slope are the easiest to flush. Wide valleys where the impoundment covers former floodplains can be less effectively flushed because the deposits tend to consolidate and are remote from the flushing channel.
- *The deployment of full or partial drawdown:* Full drawdown and empty flushing have been found to be much more effective than partial drawdown.
- *The low-level outlet facilities provided:* Worldwide experience confirms that, for effective flushing, the low-level outlets must be both low enough and of sufficient capacity to allow significant drawdown of water levels to be controlled during the time of year when flushing is undertaken. Proportionately larger outlets are required for flood-season sediment sluicing during the flood season than for sediment flushing at the outset of the flood season.

- *The scope for enhancements to flushing:* Fluctuations in water level and discharge during flushing are beneficial to the promotion of bank slumping, increasing the rate of sediment movement. Also, the deployment of lateral and longitudinal diversion channels has been successful in promoting flushing in reservoirs which are hydrologically large or contain significant proportions of deposition in areas remote from the main flushing channel.
- *Operational limitations:* Operational considerations, such as water and power demands, can inhibit the ability to flush successfully.
- *Downstream impacts:* Downstream impacts can act as a constraint in the planning and operation of sediment flushing. In some cases flushing may be ruled out, whereas sediment sluicing, which approximately preserves the seasonal distribution of sediment load, may be a practicable alternative during the early life of a reservoir.

Geographical areas suited to flushing

Erosion rate: The erosion rate depends on a complex interaction of the following factors:

- *Climate:* Precipitation and runoff, temperature, wind speed, and direction
- *Geotechnics:* Geology, volcanic, and tectonic activity, soils
- *Topography:* Slope, catchment orientation, drainage basin area, drainage density
- *Vegetation*
- *Land use and human impact*

Estimates of global average rates of denudation have ranged from 0.06 mm/year to 0.16 mm/year (Morris and Fan, 1998). This is equivalent to estimates of between 15×10^9 t/km²/year and 20×10^9 t/km²/year (Walling and Webb, 1983). Areas with sediment yield over 1,000 t/km²/year are 8.8% of the total land area and account for 69% of the total sediment load. Regions with less than 50 t/km²/year account for about half of the land area and 2.1% of the sediment yield.

Sediment yield: Sedimentation occurs in reservoirs when the eroded sediment is transported down the river system into the reservoir. The efficiency of the transport process is expressed by the sediment delivery ratio, which is the proportion of sediment eroded from the land that is discharged into rivers (Morgan and Davidson, 1986).

The sediment delivery ratio is generally higher for sediment derived from channel-type erosion which delivers sediment to the main channels of the transport system more quickly and directly than in the case of sheet erosion.

The poor correlation between sediment yield and erosion rates makes it difficult to estimate the sediment load entering a reservoir on the basis of the erosion rate within

the catchment (Morris and Fan, 1998). Most studies that have attempted to relate the delivery ratio to catchment characteristics have found that the delivery ratio decreases as the catchment area increases (Walling and Webb, 1983).

Climatic zones: An understanding of the precipitation regimes throughout the world may allow the definition of climatic zones based on temperature and precipitation regimes. This may permit the definition of areas of high and low erosion rates. It is difficult to classify distinct climatic zones as they tend to merge into one another rather than have sharp boundaries, but a number of general models have been produced.

There have been many climatic classifications produced, but one of the most common is based on the original Koppen classification (Pidwirny, 1999) with eight climatic regions based on four temperature zones and one moisture zone and the seasonal domination of air masses.

The eight Koppen climatic regions are as follows:

- Tropical wet
- Tropical wet and dry
- Tropical desert
- Mid-latitude wet
- Mid-latitude winter dry
- Mid-latitude summer dry (Mediterranean climate)
- Polar wet and dry
- Polar desert

Hydrological characteristics required for successful flushing: Experience has shown that low reservoir water levels provide the most effective conditions for sediment flushing. To allow water levels to be lowered requires confidence that rainfall can be relied upon to refill the reservoir. It follows that well-defined wet and dry seasons

will be favorable for a sediment flushing regime. Such a climate is defined by Koppen as tropical wet and dry.

Areas of the world which are best suited to reservoir flushing: It is not possible to define precisely which specific areas of the world will provide conditions for successful flushing. In reality there is a spectrum of conditions ranging from those sites where conditions are ideal to those sites which are quite unsuited to sediment flushing.

From the Koppen classification of climatic zones, the requirements for successful flushing are most likely to be met in the *Tropical Wet and Dry Region*. Conditions in another region may also be suitable for sediment flushing, namely the *Tropical Wet Region* (Figure 2).

Locations with these types of climates include:

- Parts of Central America extending into Brazil in South America.
- A region of central Africa from the Ivory Coast in the west to Sudan in the east would be suitable.
- Parts of central Asia including Pakistan, India, Nepal, China, Cambodia, Vietnam, and Thailand.

Costs and benefits of flushing facilities

With the current procedures for assessing costs and benefits to justify the financing of new projects, it is often impossible to build sediment flushing facilities when the dam is first commissioned. This is because sediment flushing (as opposed to sluicing) only becomes effective when the deposited sediment reaches the proximity of the dam, and in most cases, this will be many years after commissioning. The costs are up-front and the benefits are 20–30 years down the line – not a situation that impresses pure accountants! We need to find a way



Sediments, Flushing from Reservoirs, Figure 2 Reservoir sedimentation, Indonesia.

of putting a much higher value on sustainability in our justification procedures for the construction of dams.

The rejuvenation of existing reservoirs by the introduction of flushing facilities, particularly those which have lost between 40% and 60% of their original storage, is attractive in that costs are likely to be between 10% and 30% of the cost of new dams of a similar capacity.

Design implications for flushing facilities for new and existing reservoirs

Flushing facilities require extensive investigative work to establish their viability, and this will be required on a site-by-site basis. There are numerous stages for such investigations which include the following:

Site investigations: Flushing facilities have to be able to withstand high velocity flows with high concentrations of sediment. Such flows are highly abrasive, and expensive steel lining will normally be required to avoid undue damage to the structures. Hence, it is important that the site allows for the construction of relatively compact flushing facilities, either orifices within the dam itself or relatively short tunnels or channels. Energy dissipation works will normally be required at the downstream side, and it is an advantage if these facilities can be shared with other outlets such as high-head spillways or irrigation outlets. It is advantageous if the flushing facilities discharge to the downstream channel well away from any power station outlets as any local deposition of sediments will increase tailwater levels and reduce power output.

The reservoir itself requires a detailed survey to establish its topography. This is required to check whether the reservoir basin is a suitable shape for sediment flushing and also to provide input data for detailed modeling of the sedimentation process within the reservoir.

Hydrological investigations: It has been stated above that there are certain requirements for successful sediment flushing which are related to the amount of water available and its reliability year on year and season by season. Hence, inflows to the reservoir need to be established with confidence. This involves the acquisition of historical records of river flows going back at least 30 years and preferably longer. Records of river flows can often be extended further back in time by considering local rainfall records, which often go back a 100 years or more, and undertaking catchment modeling to convert rainfall into runoff.

The ideal situation for sediment flushing is an annual inflow of water of at least three times the volume of the reservoir (original volume in the case of existing reservoirs) and an annual hydrograph which shows distinct wet and dry seasons.

Sediment investigations: The amount and nature of the sediment entering or likely to enter the reservoir need to be established. This requires measurements over many years to establish the results with the confidence which is required. There are various approaches to this task. Most commonly sediment transport is measured at a gauging

station not too far upstream of the reservoir, and a relationship between flow rate and sediment transport rate is established. The long hydrological record is then used to compute the total amount of sediment passing the gauging station by integrating over the period of the record. There are some dangers in doing this because there is no unique relationship between flow rate and sediment transport rate for fine cohesive sediments, the quantities of sediment being determined by the amount being washed off the catchment, not the capability of the river to transport them. Bed load is difficult to measure and is often estimated as 10% of the total sediment load. An alternative approach is to calculate the bed load using established predictive techniques.

In the case of existing reservoirs, information about the amount of sediments entering the reservoir can be augmented by surveys of the amount and nature of the material settling within the reservoir. Care is required, however, to allow for the amount of, mainly fine, material which passes through the reservoir without deposition.

Bed material sampling should be undertaken in the reservoir and in the rivers which feed the reservoir. A sound knowledge of the nature of these sediments, including their size and specific gravity, is an essential requirement to provide inputs for numerical models which simulate sediment movement, see later.

Hydraulic modeling: Sophisticated numerical (computer) modeling of the way sediment is likely to behave within the reservoir and the amount and nature of the sediment which will be passed to the downstream reach is the cornerstone of any detailed evaluation of flushing facilities. One-dimensional models with quasi-two-dimensional simulation of the incised channel which develops during sediment flushing are the most appropriate tools. These models are computationally efficient and are capable of making long-term simulations, decades rather than hours or days. They have reached reliability levels which permit them to be used "cold" on new reservoirs which are only at the investigative stage. When used on existing reservoirs, they have the added benefit of measured sedimentation data for verification purposes.

Computer simulations of reservoirs ideally use representative, long-term sequences of water and sediment inflows to the reservoir. The models are capable of looking at the effectiveness of various aspects which affect reservoir sustainability over periods of up to 50 or 60 years, including:

- Measures to reduce the amount of sediments entering reservoirs such as catchment conservation or upstream storage.
- Measures to manage sediments within reservoirs such as variations in the operating rule curves for the reservoir. Rules which permit emptying of the reservoir annually promote movement of sediment toward the dam; rules which maintain high water levels ensure storage of sediments at the upstream end of the

reservoir and help to extend reservoir life albeit with the penalty of reduced water yield.

- Measures to evacuate sediment from the reservoir including dredging and sediment flushing.

Engineering and costs: The design of the civil works involved in all the options for helping to sustain reservoir capacity need to be estimated so that the best solution can be found.

System simulation modelling: System simulation modelling is required to evaluate the conflicting demands of hydropower production, irrigation, and other requirements and must be able to assess the impacts of the various reservoir operating strategies. The simulation model must be able to replicate the outputs of water and power under a range of operating strategies so that an optimal economic and technical solution may be identified. In addition, it must be possible to take account of the effects of other reservoirs upstream and downstream of the one under consideration.

Economic and financial analysis: The main aim of economic and financial analyses is to assist in the identification and selection of the most favorable sediment management option. For each option, the most important factor, from the economic viewpoint, is to define the “with” and “without” project cases. These will illustrate the net economic impact of the availability of water resources over time, including any seasonal variations. Evaluation of the impact of alternative investment phasing is also important.

The greatest challenge in the evaluation of projects which promote sustainability of reservoirs is to assign realistic values to the benefits of extending reservoir life. This is beyond the scope of this entry. Work, however, is progressing in this direction (Palmieri et al. 2003).

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Cross-references

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SLOVENIA, LAKES AND RESERVOIRS

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Wetlands in Slovenia

The Republic of Slovenia covers a surface area of 20,273 km² with a population of 2,046,976 inhabitants (~100/km²; SORS, 2010). Slovenia is situated in the southeastern part of the Alps and on the northernmost part of the Balkan Peninsula, bordering Italy in the west, Austria in the north, Hungary in the northeast, and Croatia in the east and south. Slovenia comprises four biogeographical systems: Mediterranean, Panonian, Alpine, and Dinaric. One of the main characteristics of Slovenia is a significant biological and landscape diversity. To a large extent, the main reasons of the diversity are different types of climate, geological structure, the diversified terrain, and large differences in altitude (from 0 to 2,864 m, 600 m being the average). From west to east, the climate changes from Mediterranean to continental and sub-Mediterranean, which is demonstrated by the annual amount of precipitation (between 2,000 and 3,500 mm in the Alps in the west, around 1,000 mm along the Adriatic Sea in the south, and around 700 mm in the east of the country). Slovenia's territory can thus be classified as humid. The water balance for the period 1961–1990 gave the total annual precipitation of 31.7 km³ (1,010 m³/s), the total annual evaporation of 13.2 km³ (420 m³/s), and the total annual runoff of 18.5 km³ (590 m³/s) (Kolbezen and Pristov, 1998). Taking into account the total area of 20,256 km² (a little more than the surface area of Lake Ontario in North America), the annual specific runoff is 29 l/s km².

Surface waters are present in Slovenia in many forms and places as shown by an inventory of wetlands (VGI, 2000) prepared according to the Ramsar Convention on Wetlands. Wetlands were found on more than 3,500 localities (Table 1), and only nearly one third of them is larger than 0.15 ha; their total area is 356.50 km², covering 1.74% of the surface. As much as 83% of the wetlands are human-made or human-conditioned ecosystems. Even taking into account flood areas, wetlands still cover less than 5% of the total area (VGI, 2000). Even though wetlands are rather small in size, they are diverse in form, and their role in landscape

Slovenia, Lakes and Reservoirs, Table 1 Inventory of wetlands in Slovenia according to the Ramsar Classification System for Wetland Type (From ARSO, 2003, p. 48; after VGI, 2000)

Code	Wetland type	Area (ha) (> 0.15 ha) ^a	Number of all localities ^b
<i>Marine and coastal wetlands</i>			
J	Coastal brackish/saline lagoons	74.99	4
<i>Inland wetlands</i>			
M	Permanent rivers/streams/creeks	61.77	61
N	Seasonal/intermittent/irregular rivers/streams/creeks	0	1
O	Permanent freshwater lakes (>8 ha)	456.69	2
P	Seasonal/intermittent freshwater lakes (>8 ha)	3,151.30	6
Tp	Permanent freshwater marshes/pools (<8 ha)	168.69	279
Ts	Seasonal/intermittent freshwater marshes/pools	2,959.55	171
U	Non-forested peatlands	102.81	17
Xf	Riparian meadows and forests on alluvial plains	6,184.30	28
Zg	Geothermal wetlands	0	2
Zk	Karst and other subterranean hydrological systems	305.00	1
<i>Human-made wetlands</i>			
1	Aquaculture ponds	225.31	312
2	Ponds	134.38	1,517
4	Seasonally flooded agricultural land	18,079.60	304
5	Salt exploitation sites	662.38	2
6	Water storage areas	2,700.27	72
7	Excavations	363.44	584
8	Wastewater treatment areas	16.79	1
9	Canals and drainage channels, ditches	0	156
0	No data about type	3.07	6
Sum		35,650.34	3,526

^aOnly wetlands with an area >0.15 ha contribute to the total area; the rest of them contribute only to the total number of localities

^bDoes not take into account watercourses as such, only smaller wetlands along them

and ecology is an important one. Three of them (Salt Pans in Sečovelje in 1993; the Škocjan caves in 1999; Lake Cerknica in 2006) are on the Ramsar List of Wetlands of International Importance. On the other hand, wetlands are among the most endangered ecosystems. In the past, the main reasons for diminishing of wetlands were agricultural measures and river engineering works. Documented records have shown that in the period between 1772 and 1990, more than 100,000 ha of wetlands disappeared (Beltram, 1996).

General information on lakes and reservoirs in Slovenia

In Slovenia, around 1,300 water bodies of standing waters (permanent and intermittent) have been registered in a special lexicon (Firbas, 2001, p. 3). Their total surface area is 68.93 km², covering 0.3% of the surface (below the European average). Using the same criteria for the definition of a lake (i.e., area >1 ha; constant water depth; low ratio between the inflow and the total volume), then there are (without Caspian Lake) around 500,000 natural lakes and artificial lakes (reservoirs) in Europe with a total area of around 300,000 km², covering 3% of the surface in Europe, and a total volume of 3,300 km³ – one third of the surface and one quarter of the volume is the portion of the artificial lakes (Heinonen et al., 2000).

Lakes in Slovenia are of natural or artificial origin, called a lake (Slov. *jezero*), a reservoir (Slov. *akumulacija*), a pond (Slov. *bajer*), a fish pond (Slov. *ribnik*), a muddy pond (Slov. *kal*; man-made freshwater wetland in karst and coastal Mediterranean area), and a muddy pool (Slov. *lokev*; similar to muddy pond). According to Klinar (1994) in the Slovenian language, reservoirs are typically referred to as *jezero*. A list of some important lakes and reservoirs in Slovenia is given in Table 2.

A little more than one half of the lakes in Slovenia is of natural origin. The majority of these are of glacial origin (as is the case elsewhere in Europe); in some cases, the tectonics played an important role (e.g., Lake Bled). They are remnants of glacial lakes that were not fully filled in Holocene because there were no major gravel-bed rivers flowing through them.

The largest glacial lakes in Slovenia are Lake Bohinj (3.28 km²; 92.5 million m³) and Lake Bled (1.43 km²; 25.7 million m³). The total surface area of all other permanent natural lakes together does not exceed 1.7 km². Many more small glacial lakes are placed on high mountain plateaus, mainly in the calcareous Julian Alps (seven lakes collectively called the lakes Triglavska jezera; lake Krnsko jezero) in the western part of Slovenia, where water on the karst surface is scarce. Such mountain lakes are also small and shallow lakes on Pohorje in NE Slovenia (lakes Ribniška jezera, lakes Lovrenška jezera),

Slovenia, Lakes and Reservoirs, Table 2 An overview of some lakes and reservoirs in Slovenia, listed according to their area (Compiled from Gams, 1962; ES, 1990; Firbas 2001; SORS 2010)

Lake	Area (km ²)	Depth (m)	Volume (10 ⁶ m ³)
<i>A. Natural lakes</i>			
Cerkniško jezero (Lake Cerknica; intermittent karst lake)	26 ^a	3 ^b	76.0 ^a
Bohinjsko jezero (Lake Bohinj; subalpine glacial lake)	3.28	45 ^a	92.5
Blejsko jezero (Lake Bled; glacial lake)	1.47	30 ^a	25.7
Palško jezero (intermittent karst lake)	1.25	15 ^b	10.0
Planinsko jezero (intermittent karst lake)	1.00	10 ^a	40.0 ^a
Petelinjsko jezero (intermittent karst lake)	0.74	...	...
Podpeško jezero (lake on a karst ponor)	0.012	47 ^a	...
Divje jezero (lake on a karst spring)	0.0023	15 ^a	...
Lakes Triglavsko jezero (alpine glacial lakes):			
1. Triglavsko jezero (Jezero pod Vršacem)	0.0047	5 ^b	...
2. Triglavsko jezero (Rjava mlaka)	0.012	10 ^b	...
3. Triglavsko jezero (Zeleno jezero)	0.0041	2.5 ^b	...
4. Triglavsko jezero (Jezero v Ledvici)	0.0237	15 ^a /5.7 ^b	0.135
5. Triglavsko jezero (Dvojno jezero)	0.005	8.5 ^a	...
6. Triglavsko jezero (Dvojno jezero)	0.004	5.5 ^a	...
7. Triglavsko jezero (Črno jezero)	0.0075	6 ^b	...
Krnsko jezero (alpine glacial lake)	0.050	17.6 ^a	...
Jezero na Planini pri Jezeru (alpine glacial lake)	0.0156	11 ^a	...
<i>B. Reservoirs</i>			
Ledavsko jezero (flood control, fisheries)	2.18	3 ^b	5.7
Perniško jezero (fisheries)	2.03	4.5 ^b	3.3
Velenjsko jezero (subsidence)	1.37	55 ^a /20.2 ^b	27.7
Šmartinsko jezero (flood control, fisheries)	1.07	10 ^a	6.5
Slivniško jezero (flood control, fisheries)	0.84	14.5 ^a	4.0
Vogrsko jezero (irrigation, fisheries)	0.82	20 ^a	8.5
Gajševsko jezero (flood control, irrigation, fisheries)	0.77	10 ^a 3 ^b	2.6
Jezero Molja (flood control, low flows)	0.68	12 ^a	4.3
Družmirsko jezero (subsidence)	0.55	72.8 ^a	12.0
Klivniško jezero (flood control, low flows)	0.35	14 ^a	3.7
Škalsko jezero (subsidence)	0.20	21.0 ^a	1.0
<i>C. Drava river reservoirs^d</i>			
Ptujsko jezero (1978 HPP Formin; 116 MW)	4.10	12	20.0
Ormoško jezero (1976 HPP Varaždin; 94 MW)	2.50 ^c	9	...
Vuhreško jezero (1956 HPP Vuhred; 72 MW)	2.41	23 ^a /5 ^b	11.2
Bresterniško jezero (1948 HPP Mariborski otok; 60 MW)	2.39	14.5 ^a /6 ^b	13.8
Vuzeniško jezero (1957 HPP Vuzenica; 56 MW)	1.96	10.8 ^a /4 ^b	7.5
Ožbalsko jezero (1960 HPP Ožbalt; 73 MW)	1.54	24.5 ^a /7 ^b	10.2
Dravograjsko jezero (1944 HPP Dravograd; 26 MW)	1.40	4 ^b	5.6
Falško jezero (1918 HPP Fala; 58 MW)	0.90	14 ^a /5 ^b	4.4
<i>D. Sava river reservoirs^d</i>			
Vrhovsko jezero (1993, HPP Vrhovo; 34 MW)	1.43	6 ^a	8.65
Trbojsko jezero (1986 HPP Mavčiče; 38 W)	1.00	17 ^a	...
Moščansko jezero (1952 HPP Moste; 21 MW)	0.69	50 ^a /12 ^b	8.0
Zbiljsko jezero (1954 HPP Medvode; 26 MW)	0.69	20 ^a /3 ^b	6.0
<i>E. Soča river reservoirs^d</i>			
Doblarsko jezero (1939 HPP Doblar; 30 MW & 2002 HE Doblar II; 40 MW)	0.42	32	6
Ajbsko jezero (1940 HPP Plave; 15 MW & 2002 HP Plave II; 20 MW)	0.30	12	1.1
jezero Kanalski vrh (2010 Pumped-storage HPP Avče; 185 MW)	0.11	20	2.2
Solkansko jezero (1984 HPP Solkan; 31.5 MW)	0.08	18	1.2

^aMaximum

^bAverage

^cSlovenian–Croatian border crosses the lake

^dIn brackets: year of construction, name of HPP, installed power of HPP

which occasionally formed within mountain wetlands (moors or peatlands; approx. 1,500 m a.s.l.).

Between many karst intermittent lakes in Slovenia, the most famous is the lake Cerkniško jezero (Lake Cerknica)

that forms periodically on the Cerknica polje. Other large karst lakes in Slovenia have a similar hydrologic regime of periodical flooding to the one of Lake Cerknica; however, they cannot compare to it in terms of extent and duration

of flooding. Numerous karst lakes are situated on other karst poljes, e.g., lake Planinsko jezero on the Planina polje, and the lake Palško jezero and the lake Petelinjsko jezero in the Upper Pivka valley. The Upper Pivka valley represents an interesting karst area built on a sequence of limestone and alluvium that are overlaying flysch. Over the area of 50 km², at least 15 lakes are formed periodically in karst depressions and are different from Lake Cerknica that formed on a flat bottom of the Cerknica karst polje (Ravbar and Šebela, 2004). On a karstic ponor, there is the lake Podpeško jezero with a stream flowing into the lake, and the karst ponor is located at the deepest point of 47 m; the same depth is reached in much larger glacial Lake Bohinj. On a karst spring, there lies a deep dark-colored lake Divje jezero near Idrija. When the natural karst periodic lakes are fully flooded, they represent the largest water surface in Slovenia (31.51 km²).

In Slovenia, 31.01 km² are covered by reservoirs. The largest reservoirs in Slovenia are river accumulations for hydropower plants on the rivers of Drava, Sava, and Soča (Table 2). The largest among them is Lake Ptuj with 4.1 km² and is thus larger than the largest natural Lake Bohinj (3.28 km²). Many other reservoirs are multipurpose and therefore used as, e.g., retention basins for flood control, but at the same time also for enrichment of low flows, fisheries, irrigation, and recreation.

The Šalek valley is situated in the northeastern part of Slovenia with a total area of around 150 km². Due to the underground coal (lignite) mining in Pliocene sediments, a subsidence landscape was developed (more than 110 km³ in 2004; Šterbenk et al., 2004). Recently, four montanogenic subsidence Šalek lakes (lake Velenjsko jezero, lake Družmirsko jezero, lake Škalsko jezero, lake Turistično jezero) have formed with a total surface area of lakes over 2 km² and a total volume of around 40 million m³. Together, they are larger than the famous Lake Bled.

In Sečovlje on the Adriatic coast, in the second half of the thirteenth century, salt works were established on alluvium of the Dragonja river. Nowadays, in the Sečovlje salt pans, marine salt is still harvested, even though in 1993 the area was put on the Ramsar list of wetlands, being an important ecosystem for flora and especially fauna (more than 260 bird species were counted, and the area was recognized as an Important Bird Area according to the Barcelona Convention).

For the majority of standing waters in Slovenia, which are mostly on a carbonate rock base, the major ecological problem is the excessive inflow of nutrients, above all of phosphorus and nitrate (Table 3). As a result of nutrient inflow, in many lakes blooming occurs in summer time, caused by the growing of green and blue algae. The major sources are anthropological: the point sources are untreated municipal waste waters and washing away on agricultural land is the diffuse source. In reservoirs, in some cases, additionally, there was an inflow of untreated industrial waste waters, bringing heavy metals, pesticides,

and organic compounds into the water column and sediments.

In a lifetime, a lake goes through an eutrophication cycle. Among lakes in Slovenia, typical:

- Oligotrophic lakes are the lakes Triglavska jezera
- Mesotrophic lake is Lake Bohinj and nowadays Lake Bled (after remediation measures)
- Eutrophic lake is situated in the northeast of Slovenia in lowlands along the Drava and Mura rivers
- Hypereutrophic lake was Lake Bled until mid-1960s (when its remediation started); other examples are practically all ponds and fish ponds as well as the lake Sotelsko jezero and some lakes in the Pomurje region along the Mura river
- Dystrophic (peat-bog) lakes are the lakes Lovrenška jezera on Pohorje

The majority of reservoirs on Slovenian rivers are gradually filling with silt, sand, and gravel due to a relatively high sediment production in headwaters (average specific annual sediment production rate is 250 m³/km²; sediment delivery ratio to the hydrologic network is close to 0.5) (Mikoš et al., 2004). This sedimentation process is quite obvious in reservoirs on large alluvial rivers (e.g., lake Moščansko jezero and lake Zbiljsko jezero on the Sava river; lake Ptujsko jezero on the Drava river) and in many smaller gravel-bed rivers.

Many lakes and reservoirs in Slovenia have relatively small catchment areas and the water exchange is relatively slow. In summertime, there is a profound (clear) water temperature stratification, and due to the relatively warm layer of surface water, they are of tourist interest for swimming and other water sports. Due to problems with water quality in some reservoirs (Table 3), tourism has not developed as expected. On the contrary, fisheries have become a major side purpose.

Bohinjsko jezero (Lake Bohinj)

Lake Bohinj has an area of 3.28 km², a circumference of 11.35 km, a maximum depth of 45 m, and a total volume of 92.5 million m³. It is the largest natural lake in Slovenia. Lake Bohinj has the Savica stream as the main inflow (average discharge ~ 5 m³/s) and the river Sava Bohinja as the main outflow (average discharge of 8.34 m³/s). Since there are no other substantial surface inflows, more than one third of the lake outflow is generated through submerged karst springs located along the north shore. The exchange of lake water takes on an average 4 months. The catchment area of Lake Bohinj is still not fully determined due to its karst nature; it is assumed to be around 100 km², and it is 30 times larger than the lake surface. The average annual precipitation in the lake catchment area is assumed to be 3,300 mm, and the lake exhibits a nival-pluvio hydrologic regime. During local thunderstorms or longer torrential rains, it can rise very fast, and the maximum observed difference between low and high stage is 390 cm. In the period 1919–2004 on average the

Slovenia, Lakes and Reservoirs, Table 3. Classification of selected Slovenian lakes and reservoirs into the trophic category using the OECD criteria, given for the period 1992–2010 (available data from the Environmental Agency of the Republic of Slovenia)

Trophic category	Total phosphorus Annual mean mg/m ³	Inorganic nitrogen Annual mean mg/m ³	Transparency		Chlorophyll <i>a</i>	
			Annual mean m	Minimum m	Annual mean mg/m ³	Peak value mg/m ³
Ultra-oligotrophic	≤ 4.0	≤ 200	≥ 12.0	≥ 6.0	≤ 1.0	≤ 2.5
Oligotrophic	≤ 10.0	200–400	≥ 6.0	≥ 3.0	≤ 2.5	≤ 8.0
Mesotrophic	10–35	300–650	6–3	3–1.5	2.5–8	8–25
Eutrophic	35–100	500–1500	3–1.5	1.5–0.7	8–25	25–75
Hypereutrophic	≥ 100	≥ 1500	≤ 1.5	≤ 0.7	≥ 25	≥ 75
Lake Bohinj						
1997	4.6	472	9.8	6.0	1.0	3.0
1998	3.2	477	7.9	5.6	1.7	3.5
1999	3.4	447	9.1	7.4	1.8	4.2
2000	3.3	468	9.1	4.9	1.6	3.1
2001	4.9	380	10.4	6.8	1.4	2.8
2002	3.5	450	9.8	6.4	1.4	3.3
2003	4.0	423	9.6	7.0	1.3	4.5
2004	4.7	469	8.7	4.5	1.2	3.2
2005	5.1	446	9.7	5.9	1.0	4.1
2006	3.6	485	9.8	7.5	0.7	1.7
2007	5.2	512	9.2	-	1.0	-
2008	3.6	454	9.0	-	1.0	-
2009	3.5	394	8.3	-	1.2	-
2010	4.0	369	8.5	6.0	1.2	3.9
Lake Bled						
1992	22.6	468	6.1	1.7	4.7	28.2
1993	33.0	342	5.9	1.7	4.5	18.3
1994	19.3	419	5.5	2.7	5.0	35.4
1995	15.2	477	5.9	2.5	3.4	17.2
1996	14.5	470	6.5	3.8	2.8	11.2
1997	12.7	495	8.4	4.1	2.9	13.3
1998	15.5	374	5.8	2.4	7.6	29.1
1999	17.9	312	5.0	1.2	9.3	47.4
2000	14.3	280	5.3	2.5	7.2	25.7
2001	14.3	263	6.5	2.6	7.2	24.5
2002	12.6	247	7.9	5.0	4.7	19.2
2003	12.7	252	6.7	3.5	6.2	23.4
2004	13.0	273	5.9	2.7	5.2	22.3
2005	11.7	296	7.2	4.5	3.7	12.7
2006	14.7	325	6.8	3.5	4.7	14.8
2007	12.7	350	8.3	-	2.7	-
2008	11.0	350	6.6	-	3.9	-
2009	13.2	422	5.0	-	3.7	-
2010	12.0	299	4.5	2.5	7.3	19.4
Lake Šmartinsko jezero						
2003	-	638	1.7	1.3	11.5	22.8
2004	41	862	1.2	1.1	28.0	46.0
2005	171	877	0.9	0.4	13.4	74.9
2006	33	653	1.0	0.5	16.5	44.0
2007	95	811	0.8	0.6	9.4	76.2
2008	49	706	1.1	-	9.5	-
2009	39	494	-	-	9.5	-
2010	46	681	1.0	0.6	27.6	75.1
Lake Ledavsko jezero						
2003	105	1124	0.5	0.3	62.7	425.8
2004	70	2553	0.7	0.6	63.0	138.4
2005	268	3408	0.5	0.4	37.0	83.3
2006	102	1693	0.8	0.4	36.4	57.2
2007	135	2978	0.3	0.15	61.4	205.8
2008	104	913	0.5	-	32.0	-
2009	137	1018	-	-	22.1	-
2010	70	824	0.5	0.3	32.3	67.5

lake turned into ice for 49.1 days a year. In the last two decades there is increase of the number of years without ice on the lake. The nutrient inflow into the lake is moderate because the catchment area is mainly non-urbanized and lies above the forest limit. Due to these reasons, Lake Bohinj is oligotrophic with low concentrations of phosphorus and chlorophyll *a*; only average inorganic nitrogen is somewhat above the average for oligotrophic lakes (Table 3).

Blejsko jezero (Lake Bled)

Lake Bled has an area of 1.44 km², a circumference of 6.0 km, a maximum depth of 30 m, and a total volume of 25.7 million m³. It is of paramount tourist importance for the region; it has long tourist tradition and a charming island in the middle of the lake with a church on it. The lake has only minor natural inflows from springs and one natural outflow; its average discharge from the lake is around 200 l/s. In the past, before first remediation measures to increase flow through the lake took place in 1960s, the exchange of lake water took on an average almost 4 years. It is also sheltered from winds; so the natural water circulation is limited. The catchment area of Lake Bled is 8.38 km², and it is only six times larger than the lake surface. The average annual precipitation in the lake catchment area is only 1,600 mm. The maximum observed difference between low and high stage is 56 cm, which was not even nearly reached in the last few decades. The nutrient inflow into the lake is high because the catchment area is urbanized (Bled as a tourist resort with nearly 5,500 inhabitants and 4,000 tourist beds); and pollutants come also from traffic and agricultural land. Low flow-through rate of the lake additionally reduces the self-purification capabilities of the lake. The lake is stratified with anoxic hypolimnium most of the year, except during the short period when overturn occurs and oxygen is present down to the sediment–water interface.

The water quality in the lake started to decrease early in the twentieth century with a clear decrease in 1950s. The main reason was the lack of efficient sewage, not following tourist development of the area around the lake. Inflowing nutrients stimulated the growth of phytoplankton. The growth of Cyanophyta (*Planktotrix rubescens*) not only caused long periods of “blooming” of the lake but also replenished oxygen in the lake, which started to die out. In 1964, fresh water from the Radovna river was introduced into the lake at the depth of 18 m without the expected success. Therefore, in 1982, a siphon was built to extract deep water at the rate of 240 l/s. The improvement of the sewage system in 1980s reduced the inflow of waste water by 80%. This helped Lake Bled to move from (hyper) eutrophic to mesotrophic state (Table 3).

Cerkniško jezero (Lake Cerknica)

Lake Cerknica is the largest and the best known karst intermittent lake in Slovenia. It is also an important

ornithologic ecosystem, listed among the Ramsar wetlands of international importance. In the Middle Ages, scientific ideas about the functioning of this “natural wonder,” described by J. V. Valvasor, were attracting much attention among European karst researchers. Valvasor, in his first paper (1687), gave a short basic explanation, which he further developed into a more complex, but less correct, theory (1689). The basic idea of an underground lake beneath the Cerknica one and of others inside the surrounding hills remained the same as in 1687, but the flow from one lake to another was not only through simple passages but also through at least six siphons. In the literature, authors were not recognizing the significant development in Valvasor’s ideas between both papers, as recently stressed by Shaw (2004).

Lake Cerknica can accumulate as much as 10 million m³ of water in 1 day. Regular floods can cover 20 km² or 53% of this karst polje and accumulate around 28 million m³ (Kranjc, 2002). During extreme floods, the flooded area is 26 km² and the volume 76 million m³ (Table 2). The lake is filled with floodwater within several days and then emptied in weeks. In the period 1961–1990, on an average of 79 days per year the lake was fully emptied.

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Cross-references

Europe, Lakes Review

SOURCE OF FRESHWATER

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Introduction

Lakes hold 90% of the freshwater on the surface of the planet and play an important role in maintaining the ecological health of the planet. They are also engines for economic growth, and the use of natural lakes as sources of freshwater is increasing. Rivers and aquifers, the main source of freshwater for human consumption, are now rarely capable of meeting future water demands from large cities and industrial centers due to either the unstableness of source or quality or shortage of their supply capacity. Under these circumstances, existing systems are being replaced by natural or man-made lakes or reservoirs. Already, in many cases, natural lakes have been dammed to enlarge the storage capacity and provide major water supplies.

The global water has a dichotomy: “too little water or too much.” Floods can be alleviated or mitigated, and reservoirs play their part in flood retention; droughts are now expected more often due to global warming and yet, fresh water seems abundant. Each year, on average, more than 1 km³ of surface water per capita enters lakes, rivers, and aquifers, but unfortunately, it does not always arrive where and when it is needed.

The facts remain, however, that over one billion people do not have access to clean water in a world population of six billion. According to the United Nations Population Fund, the world will begin to run out of fresh water by the year 2050 because of an estimated population growth to over nine billion. The projected growth will be in developing countries whose water resources are already stretched; worldwide, some 54% of the annual available freshwater is being used (two thirds for agriculture), but by 2025, it could be 70%, and if consumption reached the level of developed countries, it could rise to 90%. If this is so, the world’s water may run out before the world’s oil.

Table 1 shows the percentage of the world population having drinking water and the percentage range (it can be seen from as low as 38%).

Water-related diseases kill nearly 5,000 children every day; 40 billion working hours are spent carrying water each year in Africa alone (Figure 1); women in rural Africa spend an average of 26% of their time fetching water.

Today, over 500 million people live in 30 water-stretched countries, and by 2025, the UN expects 3 billion people will be in 48 stressed countries. By 2050, over 4 billion people will live in countries unable to meet the UN daily requirements of 50 l of water per person for drinking, washing, and cooking.

Lakes are among the most dramatic and pleasing features of the landscape. Nevertheless, many of the world’s lakes are in crisis with a myriad of problems that affect the quality of their water. Contamination of water and sediments from toxic and hazardous substances can occur from many sources (e.g., mercury, arsenic, cadmium, lead, chromium, as well as organic pollutants). Careful management of the lake is therefore required especially if the lake is dedicated to water supply. The World Lake Vision of the International Lake Environment Committee (ILEC)

Source of Freshwater, Table 1 Percentage of world population having drinking water (After UNICEF, 2011)

	Total	Range
Africa	65	52–85
Sub-Saharan Africa	60	26–83
Eastern and Southern Africa	59	47–87
West and Central Africa	61	46–82
Middle East and North Africa	86	76–93
Asia	87	82–96
South Asia	86	38–95
East Asia and Pacific	88	56–96
Latin America and Caribbean	93	80–97
Central and Eastern Europe/ Commonwealth of Independent States (CEE/CIS)	91	79–98
Industrial countries	100	100–100
Developing countries	79	39–92
Least developed countries	58	39–80
World	83	72–95



Source of Freshwater, Figure 1 Girl water carriers.

has recommended the following principles for managing lake water resources and other lake uses:

1. A harmonious relation between humans and nature is essential for the sustainable use of lakes.
2. A lake drainage basin is the logical starting point for planning and management – for sustainable lake use.
3. A long-term preventative approach – to prevent lake degradation.
4. Policy development and decision making for lake management – based on sound science.
5. The management of lakes for their sustainable use requires the resolution of conflicts among competing users of lake resources.
6. Citizens and other stakeholders encouraged to participate – in identifying and resolving critical lake problems.
7. Good governance based on fairness, transparency, and empowerment of all stakeholders is essential for sustainable lake use.

It is clear, therefore, that lakes in the future will be expected to play a larger part in the provision of freshwater to supplement existing supplies from rivers and groundwater.

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Cross-references

Health Aspects of Lakes and Reservoirs
Water Quality for Drinking: WHO Guidelines

SOUTH AMERICA, HOLOCENE COASTAL LAGOONS

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Introduction

The data presented in this paper come from eleven sediment cores taken in five coastal water bodies of southern Uruguay (Figure 1). The full database has been published in several papers (García-Rodríguez, 2006; Inda et al.,

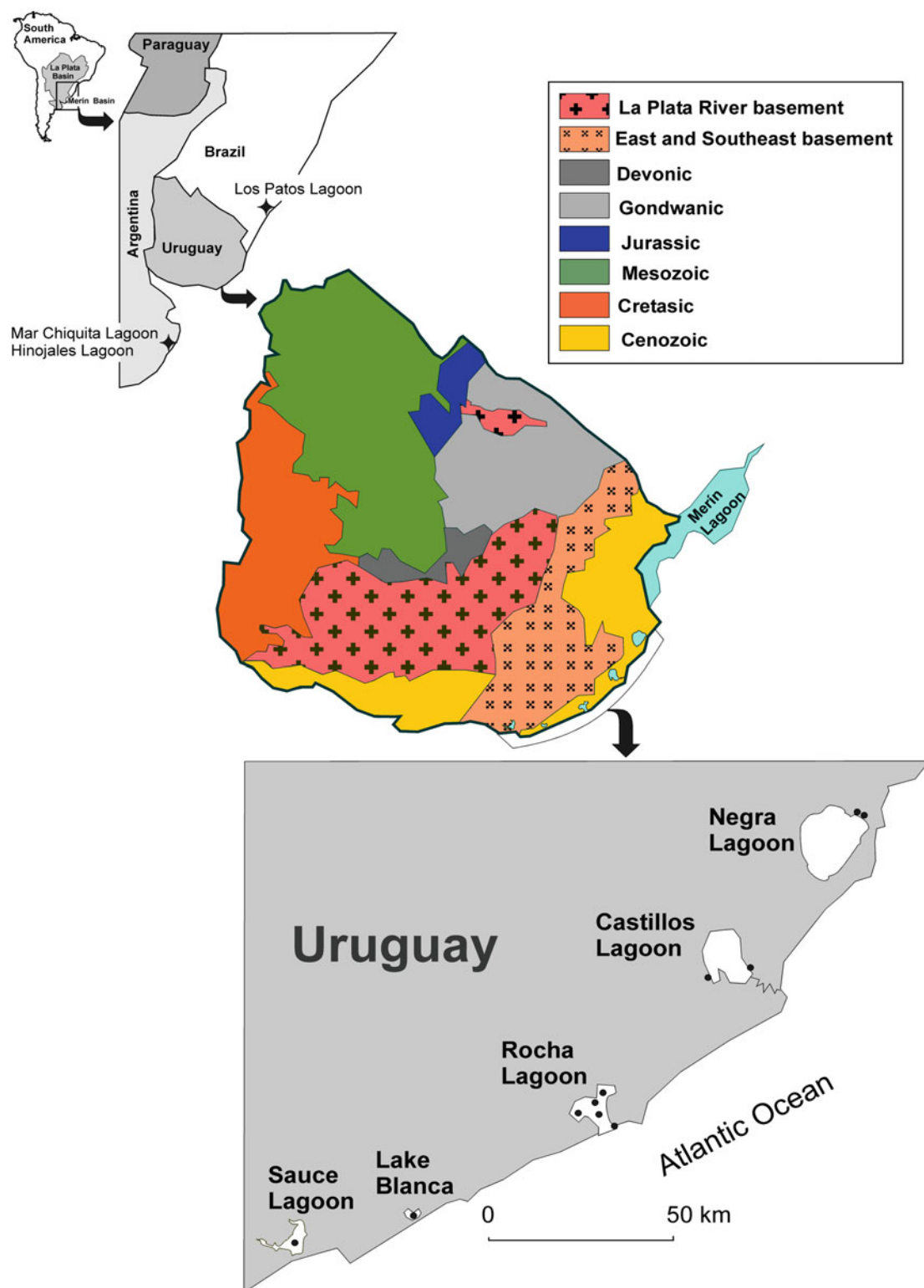
2006; del Puerto et al., 2006; García-Rodríguez et al., 2001; García-Rodríguez et al., 2002a; García-Rodríguez et al., 2002b; García Rodríguez and Witkowski, 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c; Bracco et al., 2005a; Rodríguez, 2006; del Puerto et al., 2008). In this chapter, a synthesis on the late Pleistocene and Holocene paleoenvironments is presented. The findings of the above papers are compared to other regional studies in Mar Chiquita Lagoon and Hinojales Lagoon (Argentina), and Los Patos Lagoon in Brazil (Figure 1), where similar paleoenvironmental studies have been carried out. Thus, a biogeographic overview on the late Pleistocene and Holocene coastal lagoons of the east coast of South America is presented. However, researchers of Uruguay, Argentina, and Brazil should make an effort to bring together the large amount of regional papers and publish a thorough and comprehensive review.

Study area: climate, geology, limnology, and vegetation

Uruguay is located on the east coast of South America at the lower section of the La Plata and Merín basins (Figure 1). The climate is temperate/subtropical with mean seasonal temperatures of 17°C in spring, 25°C in summer, 18°C in autumn, and 12°C in winter. However, extreme temperatures can be attained during summer (~40°C) and winter (−5°C). The prevailing winds are from the East and Northeast (warm/wet), and from the South (cool/dry). The mean historical rainfall in the southern region is ~1,100 mm year^{−1}, whereas in the north-western is ca. ~1,300 mm year^{−1}. Mean humidity is 75%, and mean cloudiness is 60%.

The geological setting consists of Cretassic, Devonian, Gondwanic, Jurassic, Mesozoic, and Cenozoic sediments, and the La Plata River and East basements. The southern region of the country corresponds to the Uruguayo-Riograndense Shield, upon which Pleistocene and Holocene formations (Libertad, Villa Dolores, and Villa Soriano) were deposited (López-Laborde et al., 2000). Thus, Holocene deposits of Uruguay are best represented in the lagoons and the wetlands. The most abundant limnological systems of the country are large rivers and a network of many small rivers and streams/creeks, which limnological state has been reviewed by Conde and Sommaruga (1999).

The coastal zone is 680 km long, from which 542 km corresponds to the La Plata River and 228 km to the ocean. The lagoons are all shallow systems (i.e., ~5 m deep) but differ in the type of connection to the ocean, elevation, and distance from the sea. Therefore, they exhibit different limnological conditions (Table 1). Both Lake Blanca and Sauce Lagoon are a drinking water source for local residents, fisheries activities are undertaken in Rocha and Castillos Lagoons, while the catchment of Negra Lagoon is used for rice fields. In addition, since the 1940s, extensive cattle/sheep grazing, forestry of both *Eucalyptus* sp. and *Pinus pinaster*, removal and



South America, Holocene Coastal Lagoons, Figure 1 *Top left:* map of South America indicating the geographical extension of La Plata and Merin basins, and political map of the Pampa region indicating the location of Mar Chiquita, Hinojales, and Los Patos Lagoon. *Center:* geological setting of Uruguay. *Bottom:* the coastal water bodies of southern Uruguay. For limnological information of the systems, see [Table 1](#).

South America, Holocene Coastal Lagoons, Table 1 Comparative limnological data for the five coastal systems. See Figure 1 for geographical location of the water bodies. Sources: Santana and Fabiano (1999); Conde and Sommaruga (1999); Jorcín (1999); Conde et al. (1999); Conde et al. (2000); Forni and Scasso (2001); Conde et al. (2002); García-Rodríguez et al. (2002a); Mazzeo et al. (2003); García-Rodríguez et al. (2004a); García-Rodríguez et al. (2004b); García-Rodríguez et al. (2004c); Bracco et al. (2005a); Rodríguez (2006)

	Sauce 34°43'S; 55°13'W	Blanca 34°53'S; 54°50'W	Rocha 34°34'S; 54°10'W	Castillos 34°21'S; 53°52'W	Negra 33°56'S; 53°33'W
Mean Z (m)	3	2	0.56	1	2.8
Maximum Z (M)	7	4	1.4	3	4
Area (km ²)	47	0.5	72	82	142
Catchment area (km ²)	722	5	1,312	1,453	720
Elevation AMSL (m)	7	3	0	0.5	7
Distance from the coast (km)	2	1	0.1	10	4
Ocean connection	no	no	direct	stream	no
Salinity range	Freshwater	Freshwater	Marine/brackish	Brackish/fresh	Freshwater
Use	Drinking water	Drinking water	Fisheries	Fisheries	Rice fields
Mean K (μS cm ⁻¹)	200	278	30	5,700	170
Mean Temp. (°C)	22	19.8	17	19.6	20
Mean Chl-a (μg l ⁻¹)	32	11	5	4.5	16.2
Mean TP (μg l ⁻¹)	250	64	105	75.2	56
Mean TN (μg l ⁻¹)	780	726	700	779	387
Mean Secchi (m)	0.7	1.2	1	0.95	0.2
Mean pH	8	7.4	7.71	7.1	8.5
Mean O ₂ (mg l ⁻¹)	10	7.1	8.5	8.3	8.2
Mean top sediment OM (%)	15	30	5	3	3

fertilization of soils, as well as construction of dams, led to several eutrophication episodes (Rodríguez, 2006; García-Rodríguez et al., 2002b).

The lagoon catchments correspond to the Pampa phytogeographic province which is characterized by slight elevations and valleys and consists mainly of wetlands, meadows, riparian forests, and palm forests of *Butia capitata*. The common wetland vegetation in southern Uruguay is represented by the genera *Alternanthera*, *Azolla*, *Bacopa*, *Cabomba*, *Ceratophyllum*, *Cyperus*, *Egeria*, *Eichornia*, *Enhydra*, *Glyceria*, *Hydrocotyle*, *Leersia*, *Lemna*, *Limnobia*, *Ludwigia*, *Luziola*, *Mikania*, *Myriophyllum*, *Oxycarum*, *Pistia*, *Polygonum*, *Potamogeton*, *Rynchospora*, *Ricciocarpus*, *Schoenoplectus*, *Scirpus*, *Solanum*, *Spirodela*, *Typha*, *Utricularia*, *Wolffiella*, and *Zizaniopsis* among others (Alonso, 1997). The grass vegetation of the meadows is characterized by *Andropogon*, *Axonopus*, *Panicum*, *Paspalum*, *Schizachyrium*, *Bothriochloa*, *Stipa*, *Piptochaetium*, and *Aristida*. Riparian forests are restricted to the littoral of small streams and are represented by *Lithraea brasiliensis*, *Schinus longifolius*, *Sapium* spp., *Sebastiania* spp., *Blepharocalyx salicifolius*, *Celtis* spp., *Syagrus romanzoffiana* (Iriarte, 2006).

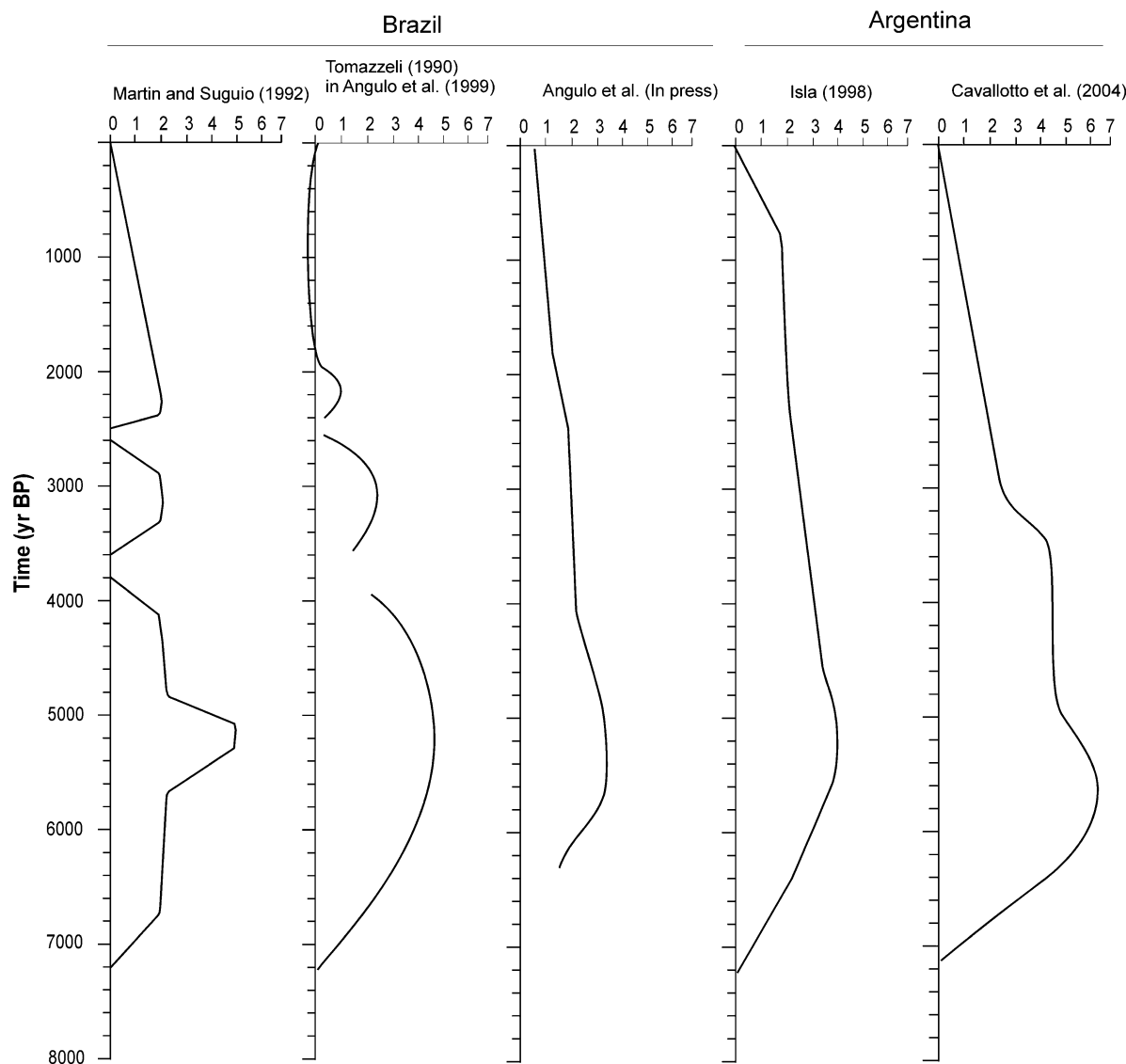
Holocene sea-level changes

The long-term development of the coastal environments depends on sea-level change, as the geomorphology and limnology of coastal lagoons are influenced by oceanographic processes. Lambeck et al. (2002) have shown that glacial/interglacial climate conditions over the past 3 Ma

have been characterized by an immense transfer of water from the ice sheets. About 50 million km³ of ice melted from ice caps, raising global sea level by ~130 m. Such changes in sea level are part of interactions between the atmosphere, oceans, ice sheets, and solid earth. The trigger for the sea-level fluctuations lies with changes in insolation, astronomical forcing, and internal feedback mechanisms such as ocean circulation or tectonics.

During the past three decades, increasing evidence on sea-level variation in the east coast of South America has been published (Isla, 1989; Martin and Suguio, 1992; Angulo and Lessa, 1997; Isla, 1998; Angulo et al., 1999; Lessa et al., 2000; Bezerra et al., 2003; Cavallotto et al., 2004; Angulo et al., 2006). Although there are certain differences between the models (Figure 2), they all propose a transgressive phase after Last Glacial Maximum; sea level was first overtaken ~7,000 year BP, maximum sea level was achieved between 6,000 and 5,200 year BP, and then there was a regressive phase until contemporary times (Figure 2). In Brazil, two submergence/emergence events (~4,000–3,900 and 2,800–2,700 year BP) were recorded by some authors (Figure 2), but others did not observe such sea-level trends. In eastern Argentina, the above two emergence/submergence events were not observed either (Isla, 1998; Cavallotto et al., 2004). The Brazilian models propose that Holocene sea level achieved a maximum between 4 and 5 m AMSL, while in Argentina, Isla (1998) proposed that maximum sea level was 4 m AMSL, whereas Cavallotto et al. (2004) observed a maximum sea level of 6.5 m AMSL. The variability in Holocene sea-level changes over different

Regional models of sea level change (m)



South America, Holocene Coastal Lagoons, Figure 2 The regional models of Holocene sea-level change for the east coast of South America.

localities may be a consequence of glacial eustasy, geoidal eustasy, tectonics, and hydrometeorological changes such as storms (Bezerra et al., 2003; Cavallotto et al., 2004). Therefore, corrections should be introduced into the curves to obtain eustatic sea-level information for different localities. Although some of the variables are relatively well known (i.e., storms), little data are available on neotectonics and geoid effects. Therefore, Cavallotto et al. (2004) concluded that it is still not convenient to apply corrections until reliable information is available. As a result, sea-level fluctuations should be considered as relative and overestimated. Even though the data on sea-level changes are not completely exact, the models

still provide interesting trends to which the Holocene paleolimnology of the coastal lagoons can be compared. However, the long-term history of coastal lagoons also depends on other factors, as the paleoenvironmental conditions of the coastal zone were shown to be a consequence of the links between sea-level changes and climate (Lambeck et al., 2002).

Late Pleistocene and Holocene paleoclimate

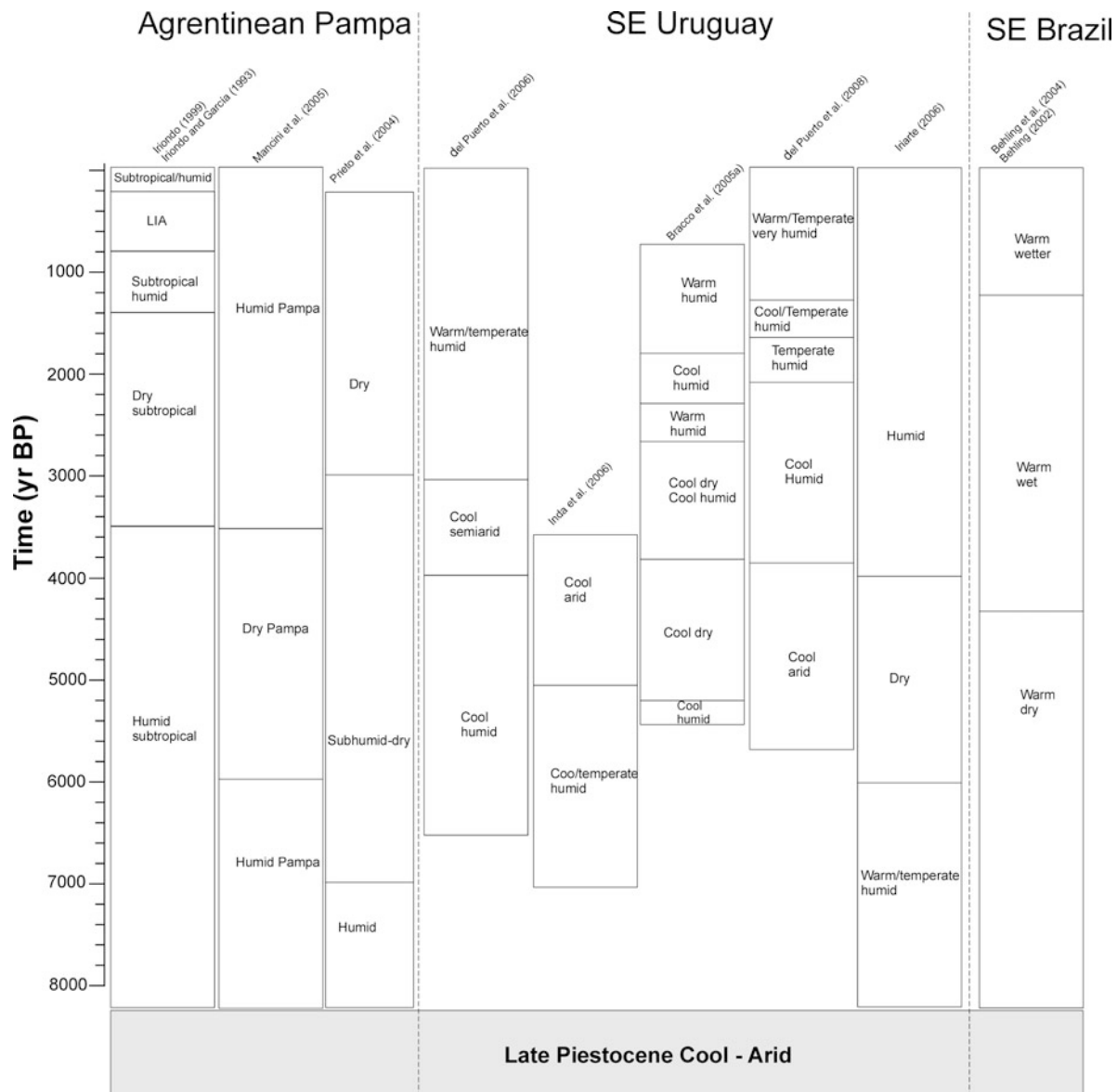
Information on climate change is particularly important for developing countries, such as those of South America, as they are particularly vulnerable to climatic changes (e.g., El Niño Southern Oscillations, Ravindranath and

Sathaye, 2002). Instrumental data on climatic variability are only available since the beginning of the twentieth century. However, these records are too short to detect decade-to-century or millennia climate variability (Xiong and Palmer, 2000). Thus, to hindcast Pleistocene/Holocene climate changes, proxy data derived from geological, chemical, or biological records are needed.

The Late Pleistocene and Holocene paleoclimatic trends in the Pampa phytogeographic region were characterized by a transition from cool and dry to temperate/subtropical and humid. During the Holocene, a high variability in climatic conditions was observed by

different authors, as different climatic trends can be found in the literature (Figure 3).

Kröhling and Iriondo (1999), Iriondo (1999), and Iriondo and García (1993) proposed the following climatic episodes for the Argentinean Pampa: (1) 18,000–8,500 year BP, Arid and cool; (2) 8,500–3,500 year BP, humid subtropical; (3) 3,500–1,000 year BP, dry subtropical; (4) LIA, between 800 and 200 year BP; (5) Present climate, nineteenth and twentieth century, subtropical humid. However, Mancini et al. (2005) reviewed 42 published records of pollen in the Pampa region and inferred the occurrence of dry episode about 6,000 year BP. In addition by ~4,000 year BP, a dry



South America, Holocene Coastal Lagoons, Figure 3 Late Pleistocene and Holocene paleoclimatic trends for the Pampa region.

Pampa with occurrence of halophytic vegetation was still observed. Prieto et al. (2004) and Prieto (2000) inferred cool dry conditions from late Pleistocene to 7,000 year BP, when a shift to subhumid–dry climate was observed, but climate became even dryer during the late Holocene.

Paleoclimatic data from Uruguay indicate differences with not only the Argentinean Pampa but also intrinsic variability between localities of the country (Figure 3). For example, Bracco et al. (2005a), Iriarte (2006), del Puerto et al. (2006), and Inda et al. (2006) observed the occurrence of both dry and humid conditions during early Holocene. Such discrepancies could be explained because of the high variability in climatic conditions. However, the late Holocene appears to be characterized by the onset of warm, humid, and more stable conditions (Figure 3).

In Brazil, authors reported paleoclimatic trends that further suggest high climatic variability within the Pampa phytogeographic region during mid-Holocene (Hilgert-Cordeiro and Lorscheitter, 1994; Behling, 1997; Behling, 1998; Behling, 2002; Behling et al., 2004). For instance, Behling et al. (2004) studied a high-resolution pollen record from southern Brazil, and Behling (2002) reviewed 14 pollen records from southern Brazil. They proposed cool and dry conditions for the late Pleistocene, warm and dry for the early and mid-Holocene, while conditions similar to the modern climate were established after ~4,300 year BP, and especially after 1,500–1,000 year BP (Figure 3).

Most of the above literature deals with pollen and opal phytoliths as proxies for climate. Thus, they also provide valuable information on the Holocene vegetation of the terrestrial environments and the catchments of the coastal aquatic systems. The dry and cool climatic events (early Holocene) were characterized by dominance of C3 grasslands (i.e., pooid phytoliths) and halophytic vegetation such as Asteraceae, Amaranthaceae, and Chenopodiaceae (Bracco et al., 2005a; Stutz, 2006; Iriarte, 2006; del Puerto et al., 2008). During the more humid episodes of the late Holocene, increases in wetland taxa of Cyperaceae were recorded with concomitant increases in C4 grasslands (i.e., panicoid and chloridoid phytoliths). The relationship between paleoenvironmental conditions of coastal systems and pollen associations was tested by Stutz and Prieto (2003), using recent samples in the Pampa region (Buenos Aires, Argentina). They developed a model of vegetation distribution in relation to the environmental conditions. Such a model has shown that the plant associations exhibited distinct pollen assemblages that conform the paleoclimatic trends: (1) the psammophytic community, characterized by Poaceae, Cyperaceae, and maximum values of psammophytic types; (2) the halophytic community, characterized by maximum values of Chenopodiaceae; and (3) the freshwater community, represented by maximum values of both Cyperaceae and hydrophytic types and by Poaceae.

All the papers on paleoclimatic data discussed here agree with cool and arid conditions for Late Pleistocene. The Holocene (and especially early to mid-Holocene)

was characterized by high variability in climatic conditions, while most authors observed the onset of humid conditions during the late Holocene.

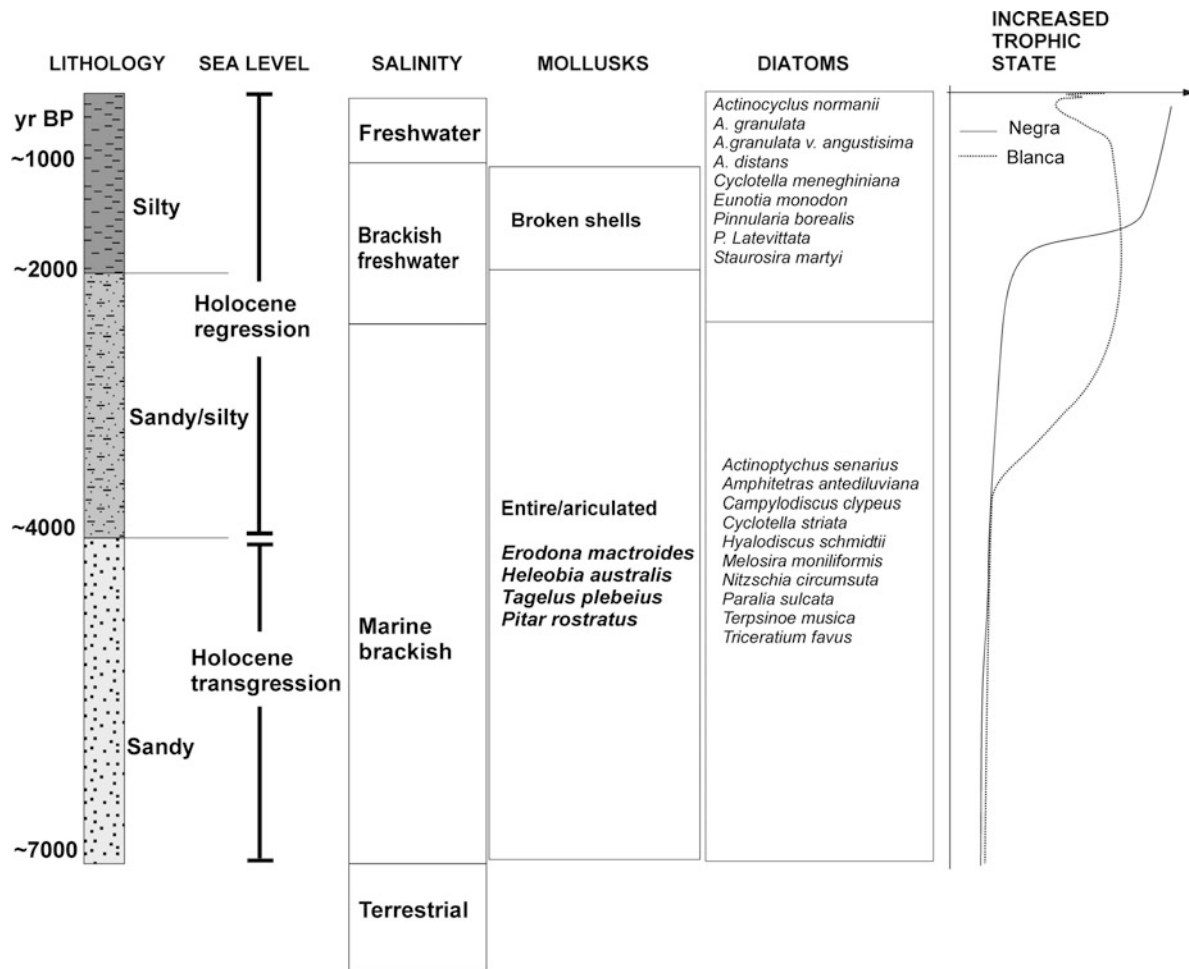
Holocene paleolimnology of coastal lagoons

The limnology of aquatic systems is strongly related to the climatic/seasonal conditions. In the case of coastal systems, marine intrusions (e.g., storms, tidal influence) also moderate the limnological conditions (Hilmer and Bate, 1990; Conde et al., 1999; Conde et al., 2000; Conde et al., 2002; Hassan et al., 2006). In this sense, Holocene sea-level changes play a major role in influencing the paleolimnological conditions as well (Sprechmann, 1978; Oschmann et al., 1999; García-Rodríguez et al., 2001; García-Rodríguez et al., 2002b; García Rodríguez and Witkowski, 2003; Espinosa et al., 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c; Stutz et al., 2006). Thus, the paleoclimatic, paleolimnological, and paleoceanographic interactions are thought to determine the sedimentary, chemical, and biological structure of coastal lagoons.

Sedimentary aspects

The sediment deposition/resuspension in coastal lagoons is related to the energy of the physical processes of the water column (i.e., turbulence, tidal currents, wave action). In those areas where high-energy physical processes occur, coarse sediment particles are observed (i.e., sand). On the other hand, low-energy environments are dominated by fine sediment particles (i.e., silt, clay, mud) (Isla and Espinosa, 1995; Bersezio et al., 1999; Kjær, 1999; Klingbeil et al., 1999; Wang and Ke, 1999; Stewart et al., 2000). Wang and Ke (1999) undertook a detailed study in the coastal zone in China and demonstrated that there is a close relationship between the energy and the sediment composition. They observed that the supratidal section was dominated by silt/clay, the intertidal section by silt/sand, while the beach was dominated by sand. A similar sediment gradient can also be found in Uruguay (e.g., Rocha Lagoon) (Corbellini, 1983; Sommaruga and Conde, 1990) or Argentina (e.g., Mar Chiquita Lagoon) (Isla and Espinosa, 1995). With this in mind, the different lithological units of a sediment core reflect the environment in which they were deposited. Therefore, those lithological units dominated by sand will represent high-energy environments (e.g., beaches), while those dominated by silt/clay will indicate low-energy environments (e.g., lacustrine systems).

The eleven sediment cores retrieved from the five coastal water bodies in southern Uruguay (Figure 1) showed a similar lithological composition, which can be summarized as follows. During the first Holocene marine transgression (i.e., ~7,000–4,000 year BP), high relative percentages of sandy sediments were observed (Figure 4). After the regressive phase until ~2,000 year BP, when sea level was ~2 m AMSL, increases in sand/silt sediments were recorded. During the last stage of the



South America, Holocene Coastal Lagoons, Figure 4 Generalized model of paleolimnological changes in the coastal lagoons of southern Uruguay during the Holocene. For detailed information, see García-Rodríguez (2006); Inda et al. (2006); del Puerto et al. (2006); García-Rodríguez et al. (2002b); García Rodríguez and Witkowski, (2003); García-Rodríguez et al. (2004a); García-Rodríguez et al. (2004b); García-Rodríguez et al. (2004c); Bracco et al. (2005a).

regressive phase (i.e., after 2,000 year BP) as sea level continued to decrease, dominance of silt/sand was observed (García-Rodríguez et al., 2001; García-Rodríguez et al., 2002b; García Rodríguez and Witkowski, 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c). Similar lithological composition of sediment cores was recorded in Mar Chiquita Lagoon and Hinojales Lagoon in Buenos Aires Province, Argentina (Stutz et al., 2006), but also in Los Patos Lagoon in Rio Grande do Sul, Brazil (Oschmann et al., 1999, Figure 1). The above facts indicate that there is a strong relationship between lithology and sea-level changes, and therefore, the paleosalinity of coastal lagoons (Figure 4). In addition, the lithological units of the sediment cores of the coastal lagoons also contain mollusk shells which corroborate the relationship between lithology and paleosalinity (Oschmann et al.,

1999; García-Rodríguez et al., 2001; García-Rodríguez et al., 2002b; García Rodríguez and Witkowski, 2003; Espinosa et al., 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c). That is, during the first Holocene marine transgression, high abundances of entire/articulated remains of marine/brackish mollusks were observed. The most representative species with their optimum salinity ranges (Sprechmann, 1978; Aguirre and Urrutia, 2002; Bracco et al., 2005b) included: *Heleobia australis* (0.5–6‰), *Erodona mactroides* (10–18‰), *Tagelus plebeius* (0.5–29‰) and *Pitar rostratus* (18–30‰). After ~2,000 year BP (i.e., during the last stages of the regression), as salinity levels decreased, a reduced content of entire articulated mollusk shells were observed. Similar data on mollusk have been reported for both Los Patos Lagoon and Mar Chiquita Lagoon (Oschmann et al., 1999; Stutz et al., 2006, Figure 1).

Chemical aspects

Knowledge on Holocene trophic state of coastal lagoons is very important, as it provides with information on both eutrophication and oligotrophication episodes. The trophic state index is often expressed as total carbon, total nitrogen, and total phosphorus content. In addition to this, the C/N ratio allows to discern between different sources of organic matter (i.e., terrestrial >30, macrophytes ~12, plankton ~7, bacteria ~4) (Müller and Mathesius, 1999; Kaushal and Binford, 1999; Meyers and Lallier-Vergès, 1999), and thus, a precise balance on the relative importance of autochthonous and allochthonous energy inputs can be determined. Since coastal lagoons are subject to many external inputs, because of the occurrence of erosion processes in the coastal zone, the composition of the organic matter in a sedimentary profile is a very useful tool to reconstruct such processes.

Both transgressions and regressions appear to be the most important factors influencing not only the salinity but also the trophic state of coastal lagoons (García-Rodríguez et al., 2001; García-Rodríguez et al., 2002b; García Rodríguez and Witkowski, 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c; Bracco et al., 2005a). During Holocene transgressive episodes, relatively low trophic states were inferred for the coastal lagoons of southern Uruguay, as low organic matter, total carbon, total nitrogen, and total phosphorus were recorded. This is because the trophic state of inland systems is usually higher than that of the open ocean because of both external inputs as well as internal loading (Margalef, 1983). On the other hand, during regressive episodes, higher content of nutrients and organic matter were recorded because of the increased runoff/erosion (as C/N values of ~30 indicated inputs of terrestrial components) (García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b), while regressions took place. Therefore, an inverse relationship between trophic state and sea-level variation (and paleosalinity levels) was inferred for the Holocene coastal lagoons of the east coast of South America. Moreover, Inda et al. (2006) determined that during the first Holocene marine transgression (i.e., 7,000–4,000 year BP), both higher frequency and lower amplitude sea-level oscillations than those reported in the regional models of sea-level change also moderated the trophic state of Rocha Lagoon (Figure 1). That is, during marine/brackish stages, decreases in trophic state were recorded. On the other hand, low trophic state was associated to brackish/freshwater episodes.

During the final stages of the Holocene regression (i.e., after 1,500 year BP), some of the coastal lagoons became separate from the ocean (e.g., Lake Blanca [del Puerto et al., 2006; García-Rodríguez et al., 2004a] and Negra Lagoon [Bracco et al., 2005a]), until the onset of freshwater systems. During the separation process, because of the combined effect of a regressive phase and either a climatic amelioration or deterioration, changes in

trophic state were observed (García-Rodríguez et al., 2004a; del Puerto et al., 2006). In the case of Lake Blanca, the separation process began by the little ice age (LIA, by ~800–200 year BP) (Iriondo and García, 1993). Both nutrient depletion and a decrease in trophic state (indicated with a dashed line in Figure 4) were observed during such a climatic deterioration. Negra Lagoon became separate from the ocean by ~1,700 year BP (Bracco et al., 2005a) at which time a climatic amelioration was inferred (Figure 3). Consequently, eutrophication intensified (depicted with a solid line in Figure 4), as the highest organic matter contents in the history of the water body were measured. Thus, the trophic state of coastal systems during the separation process from the ocean appears to be controlled by both climate and sea-level variation.

Biological aspects

The microfossils deposited in sedimentary profiles are excellent indicators of the paleoenvironmental conditions. Among them, diatoms have been often utilized in paleoecological studies of coastal environments, as the silica structures are resilient to paleoenvironmental degradation (Frenguelli, 1941; Frenguelli, 1945; Müller-Melchers, 1945; Maidana, 1994; Witkowski, 1994; Denys and de Wolf, 1999; Metzeltin and García Rodríguez, 2003; Espinosa et al., 2003; Hassan et al., 2006). In addition to diatoms, other silica remains, such as chrysophyte cysts, have been often utilized in paleoenvironmental reconstructions as well (Smol, 1985; Cumming et al., 1993; Lotter et al., 1997, 1998; Karst and Smol, 2000; Forrest et al., 2002). Both diatoms and chrysophyte cysts are very good indicators of several environmental variables. However, in the case of Holocene coastal lagoons, they were shown to reliably mirror the paleosalinity changes caused by sea-level variations (García Rodríguez and Witkowski, 2003; Espinosa et al., 2003; García-Rodríguez et al., 2004a; García-Rodríguez et al., 2004b; García-Rodríguez et al., 2004c; Hassan et al., 2006; Vilanova et al., 2006). In addition to this, the ratio of chrysophyte cysts to diatoms [first introduced by Smol (1985) to track trophic state changes in freshwater systems] was shown to be a reliable and simple tool to infer paleosalinity changes in coastal lagoons (García-Rodríguez, 2006). Since chrysophytes are rarely found in marine environments (Duff et al., 1995; Rull and Vegas-Vilarrúbia, 2000), their relative abundance in coastal systems changes following salinity levels (i.e., ratios of chrysophyte cysts to diatoms increase with a decrease in salinity). Thus, by tracking changes in this simple ratio in a sediment core, shifts in paleosalinities could be reconstructed.

The major environmental change during the early Holocene in the east coast of South America was the occurrence of the marine transgression (Figure 3). Consequently, there was a transition from terrestrial systems to the formation of coastal lagoons because of the high sea-level stand (Figure 3). During this stage, aquatic systems exhibited marine/brackish conditions as indicated by high

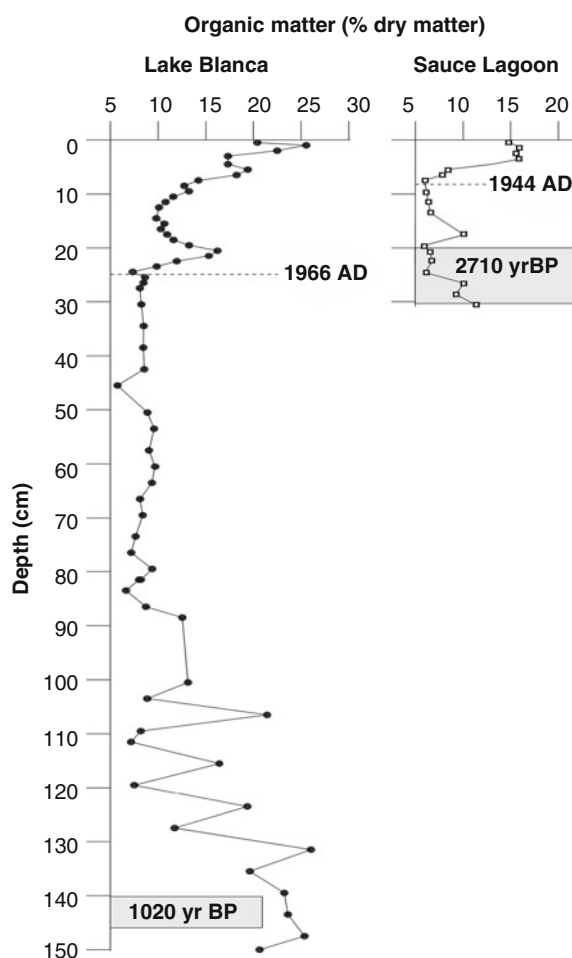
abundances of marine/brackish diatoms (Figure 4). In addition, very low values or even absence of chrysophyte cysts were detected (García-Rodríguez, 2006). As the Holocene regressive phase started after ~5,000 year BP, decreases in salinity levels were detected, thus leading to the establishment of brackish/freshwater systems by ~2,000 year BP (Figure 4). Diatom flora was shown to be dominated by brackish/freshwater species (Figure 4), and concomitant increases in chrysophyte cysts were observed (García-Rodríguez, 2006).

The time and magnitude of the transition from marine/brackish to brackish/freshwater was related to the elevation, distance from the shore (see Table 1), possible river/steam freshwater discharges, morphometry, and catchment geomorphology. For instance, Rocha Lagoon (Figure 1) is presently separated from the sea by a sand bar that opens several times a year if water level increases above ~1.3 m (Conde and Sommaruga, 1999). Thus, this water body is classified as a marine/brackish system, although freshwater pulses occur during the winter. For this reason, the water body never achieved a full brackish/freshwater stage during the Holocene. Lake Blanca and Negra Lagoon are respectively elevated 4 m and 8 m AMSL, and they do not open to the sea (Table 1). Both systems exhibited marine/brackish conditions during the early Holocene, brackish/freshwater during the mid-Holocene, but a full freshwater system was only established after ~1,000 year BP, when sea level was about +1 m AMSL (García-Rodríguez et al., 2004a; Bracco et al., 2005a). During the full freshwater stage, dominance of freshwater diatoms was recorded (Figure 4).

Palynological studies provide information not only on the macrophyte associations but also on the nonsiliceous microalgae, which can be ultimately related to the paleosalinity changes. Stutz et al. (2006) reconstructed the Holocene pollen associations of Mar Chiquita Lagoon (Figure 1) and observed that prior to 5,000 year BP, both psammophytic/halophytic associations developed on extensive sandy flats. Between 4,000 and 2,500 year BP, during a period of sea-level stabilization, similar halophytic communities were observed, but after 2,500 year BP, as sea level continued to decrease, freshwater associations were established. In addition, freshwater microalgae (*Scenedesmus*, *Zignemataceae*, *Botryococcus*, and *Gloetrichia*) increased relative abundances after ~2,500 year BP, thus indicating decreases in paleosalinities. del Puerto et al. (2008) observed similar changes in pollen associations in Negra Lagoon (Figure 1), which, combined with a previous record of diatoms and chrysophyte cysts, provided an outstanding record of paleoenvironmental information. This highlights that studies combining both siliceous and nonsiliceous microalgae represent an exceptional and relatively cheap approach for paleoenvironmental studies.

Human impacts in recent times

The Anthropocene is the most recent geological epoch. Smol et al. (2005) analyzed 55 sediment cores from lakes



South America, Holocene Coastal Lagoons, Figure 5 Changes in organic matter content in sediment cores taken from two drinking water sources. For location of both systems, see Figure 1. Data from Lake Blanca reproduced with kind permission of Springer Science and Business Media (García-Rodríguez et al., 2002b, Figure 3).

in the circumpolar Arctic. They observed that because of climate warming through lengthening of the summer growing season and associated limnological changes, a widespread species changes in algae and invertebrate associations took place since ~1850 AD. Thus, the Anthropocene is characterized by the human modification of biogeochemical cycles and climate. Anthropogenic changes in the coastal systems of Uruguay are best represented in Sauce Lagoon and Lake Blanca. Both systems are a drinking water source for local residents (Table 1). The paleolimnological evidence indicates that once the human activities started, eutrophication episodes were observed (Figure 5). Sauce Lagoon (elevation 7 m, distance from the sea 2 km, Table 1) was still connected to the sea during late Holocene (Rodríguez, 2006), and only after the construction of a dam in 1944,

a freshwater system was established. The system became a reservoir and the residence time increased. Concomitant increases in organic matter and nutrients, together with changes in diatom composition, were recorded (Rodríguez et al., 2006). In Lake Blanca, forestry activities in the catchment by ~1960 AD (García-Rodríguez et al., 2002b) led to increased phosphorus inputs and organic matter content (Figure 5). Therefore, after the drinking water facilities became operative, eutrophication intensified in both cases. In addition, microalgae blooms and problems associated to the odor and taste of the water were reported by the local residents. In this sense, paleolimnological techniques provided important historical information to help us understand the eutrophication process after human impacts. Such information would have been otherwise unobtainable, as limnology as a science in Uruguay dates only from early 1980s. Thus, particularly in developing countries, paleolimnological studies are necessary to provide baseline limnological data and assist managers and decision makers toward a sustainable use of our aquatic systems.

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Cross-references

[Coastal Lagoons](#)
[Estuarine Hydrology](#)
[Lakes as Archives of Earth History](#)
[Paleolakes](#)
[Paleolimnology](#)
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SOUTH AMERICA, LAKES REVIEW

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Introduction

With an area of about 17,826,530 km² (6,878,521 mi²), South America extends from about 12°N to 54°S, and 35°W to 81°W. On the W., it is bordered by the Pacific and on the E., by the Atlantic, with the Caribbean Sea to the N. It is separated in the S. from Antarctica by the Drake Strait. To the N., it is linked to Central America by the Isthmus of Panama. Its highest mountain is Cerro Aconcagua in Argentina (6,960 m; 22,834 ft). The continent is divided by the equator which runs from Ecuador through Brazil to the mouth of the Amazon.

Geologically, the continent is part of the pre-plate-tectonic breakup of Gondwanaland which began about 245 M years ago with fractures along the NE and eastern margins, separating it from West Africa, associated with subduction along the Pacific margin that created the 9,000-km-long Andean orogenic and volcanic belts. This Andean belt swings around in the N to face the Caribbean which had a complex history of convergence and divergence.

The lakes of South America reflect this geotectonic history, as well as its meteorological diversity, from the tropics to the subarctic and from sea level to the endorheic region of the Andean “altiplano” (high plateau, over 2,800 m elevation), which covers 220,000 km². More than 99.8% of the exorheic drainage is into the Atlantic (Figure 1).

Classification

South America’s lakes may be categorized generically as follows:

(a) Structural:

For example, *Lake Titicaca*, 8,110 km² (3,130 mi²), partly in Peru, partly in Bolivia, is at



South America, Lakes Review, Figure 1 Distribution of lakes in South America. 1, Fagnano; 2, Argentino; 3, Viedma; 4, San Martín; 5, Buenos Aires; 6, Colhue Huapi; 7, O'Higgins; 8, Nahuel Huapi; 9, Llanquihue; 10, Musters; 11, General Carrera; 12, Mar Chiquita; 13, Mirim; 14, Patos; 15, Yacyreth; 16, Posadas; 17, Taipul; 18, Poopo; 19, Titicaca; 20, Peru; 21, Tucurui; 22, Suriname; 23, Maracaibo; 24, Alberto Lleras.

3,812 m elevation; freshwater; fed by snow-melt rivers from the Andes.

Lake Poopó (Pampa Aullagas), in the central plateau, is highly saline, being in a rain-shadow area and having no outlet. Other "salars" (e.g., Salar de

Uyuni, S. de Coipasa) and salt lakes are numerous in the "puna" or high Plateau (nearly 4,000 m).

Lake Lauricochoa, Peru, about 6 km long, feeding into the Marañón R., and hence the Amazon, one of its headwaters.

Lake Mar Chiquita, Argentina, about 75 km long, seasonally to 150 km (fed by Rio Dulce from the central Andes).

Lake Musters and Lake Colhué Huapi, in central Patagonia, are fed by waters from the Eastern Andes, together with a large peppering of smaller lakes throughout the Pampas region of Patagonia that appear to be fed by artesian sources.

Laguna Ginebra, in northern Bolivia, together with a large number of smaller bodies and swamps of the Llanos de Mojos, appear also along the eastern Andean foothills.

(b) *Volcanic*:

Crater lakes are of necessity small but fairly numerous in the low-frequency eruptive centers of the Andes. Certain instances are at very high elevations and are capped by perennial snow. In the unusual event of renewed activity, catastrophic lahars (mudflows) are initiated.

(c) *Glacial*:

For example, Sea-level outlet glaciers form small lakes due to the block of meltwaters on the Pacific side of Patagonia (in Chile); several areas are set aside as national parks.

The Pleistocene glaciated valleys of the Atlantic (Argentine) side, e.g., Lake Nahuel Huapi (Argentina, about 65 km long, a national reserve). Several lakes overlap the Chilean border (and hence have two names), e.g., L. General Carrera/L. Buenos Aires, L. O'Higgins/L. San Martin. Lago Viedma is entirely on the Atlantic side, as is the L. Argentine (both the latter are part of a national glacier park).

(d) *Coastal embayment*, tectonically modified:

For example, *Lake Maracaibo*, 560 mi², a brackish, mixed marine and freshwater depression.

Coastal tectonics is also a factor farther W. in Bolivia, producing, e.g., the Cienaga Grande ("Big Lagoon") and others around Cartagena and Barranquilla (mouth of Magdalena R.). Farther upstream, a subsidence area has created a large number of smaller lagoons and swamps.

(e) *Coastal lagoons*, barred by littoral drift and dunes:

For example, Lagoa dos Patos and L. Mirim (Rio Grande do Sul, Brazil); also at Cabo Frio (L. de Afaruama), and Cabo de São Thomé (L. Feid). More are clustered at the delta of the Rio Doce where cyclic sedimentation has built up a sequence of beach ridges that serve to isolate the lakes.

(f) *Amazonian seasonal lakes*: Maximum rate of discharge about 100×10^3 m³/s.

Much of the Amazon valley becomes a series of major ephemeral lakes during the snow-melt season in the Andes (southern summer). Prior to the plate-tectonic separation from West Africa, the Amazon flowed westward, a major drainage reversal feature.

(g) *Dams and reservoirs*:

Two of the world's highest dams are in South America, both in Columbia – the Alberto Lleras C.

(243 m) and La Esmeralda (237 m) – and three of the world's largest embankment dams – Tucuui in Brazil (85,200 m³), Yacireta in Argentina (81,000 m³), and Guri in Venezuela (70,000 m³). Guri retains the seventh largest reservoir in the world (135,000 million cubic meters). Fifteenth largest is the Serra da Mesa reservoir in Brazil with 54,400 million cubic meters (according to the "World Almanac" for 2003). ["Represa" is Portuguese for reservoir; "embalse" in Spanish.]

Suriname, the former Dutch colony, has several moderate-sized reservoirs, one having the distinction of being named after a professor of Hydrology: "Professor van Blommerstein Meer."

There is an *International Commission on Large Dams*, which also lists the world's largest capacity hydroelectric dams, as follows:

- #3. Itaipu (on Paraná R. near Iguassu Falls, Brazil/Paraguay, 7,400 MW; potential, 13,320 MW)
- #5. Guri (Raoul Leoni, Venezuela, 10,300 MW)
- #6. Tucurui (Brazil, 2,640 MW; potential, 7,260 MW)
- #8. Corpus Posadas (on Paraná R. above Apipé Rapids; potential, 6,000 MW)
- #12. Xingo (on the Xingu, a major tributary of the Amazon, Brazil, 3,012 MW potential, 5,020 MW)
- #19. Paulo Alfonso L. (Brazil, 1,524 MW; potential 3,409 MW)
- #20. Pati (Brazil; potential, 3,500 MW)
- #21. Ilha Salteira (Brazil, 3,200 MW)
- #22. Chapecón (Brazil; potential, 3,000 MW)

Conclusion

South America, after Australia, has the fewest and least capacity of the world's lakes, in proportion to its area, although it has the world's largest river, the Amazon (length about 6,400 km; annual discharge to Atlantic Ocean: 6,930 km³). Most of the drainage is exorheic, very little endorheic, or arheic.

It is too soon to measure the effects of major deforestation and uncontrolled logging on sedimentation rates and the consequent filling of South American lakes and reservoirs. However, the red color of the eroded soils is readily apparent from the air, e.g., below the new highway crossings on Amazonian rivers and on other tropical rivers out into the Atlantic (personal observations: RWF).

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Cross-references

[Amazon Lakes](#)
[Poopó Lake, Bolivia](#)
[Titicaca Lake](#)

STRATIFICATION AND MIXING IN TROPICAL AFRICAN LAKES

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Introduction

The lakes in tropical eastern Africa are concentrated in the Eastern and Western Rift Valleys. The Eastern Rift Valley, which extends from northern Tanzania into the Danakil Depression in Ethiopia, is semiarid. The majority of the lakes within it are closed basin lakes, that is, they receive water from incoming rivers and precipitation but have no outlet. They tend to be salty, sometimes saltier than seawater, due to evaporative concentration of their waters. The lakes which are near the rift boundaries are long, narrow, and tens of meters deep, whereas those away from the boundaries are primarily pans that are tens of kilometers squared in surface area and generally a few meters deep. A number of small crater lakes formed when magma, close to the Earth's surface, superheated the overlying groundwater causing an explosion. Lakes in the Western Rift Valley are exposed to a wetter climate and many have outlets and are fresh. The larger ones are graben lakes, that is, lakes created as the continental plates separated. Due to their large size, at least 200-km long and 50–1,500-m deep, they are called the African Great Lakes. Lake Tanganyika is the largest of these lakes, 650-km long and over 1,000-m deep. Only Lake Baikal in Siberia, also a graben lake, is deeper. Lake Turkana is the only lake in the Eastern Rift Valley which is classified as a Great Lake. Due to volcanism in the area, crater lakes are numerous with distinctive chemical compositions. Lake Kivu is in part fed by subterranean springs with high concentrations of CO₂. Consequently, even though it has an outlet, it is chemically stratified. Lake Victoria, the second largest lake by surface area on Earth, is located between the two rift valleys. Formed by the combination of uplift and subsidence, at 80-m deep it is the shallowest of the African Great Lakes. Its climate is complex, with the eastern side arid and the western and northern sides receiving high precipitation. The stratification and mixing of lakes in tropical Africa are influenced by their geological setting particularly as it influences their depth.

The physical properties of water at warm temperatures provide another important influence. That is, at temperatures above 20°C, temperature differences of a degree or two cause density differences which are larger than would be found for temperature differences of 5°C or 6°C at cooler temperatures. Thus, warming of the upper waters in the day causes appreciable increases in density. Night-time cooling, however, can erase the density stratification. The minimum temperatures in lakes at all latitudes are set, in part, by minimum air temperatures, which are warm and with minimal annual variation in the tropics. For the lakes closest to the equator, minimum air temperatures are only

a few degrees cooler than maxima and the temperature gradient between surface and bottom waters is small. Due to the warm surface temperatures, evaporation rates are high. As a result of the high evaporation rates, mixing due to wind or cooling can extend to deeper depths than in lakes outside the tropics, and conditions are less favorable for the establishment of seasonal stratification such as that found in temperate and arctic lakes. In consequence, the shallow lakes exposed to wind tend to stratify and mix to the bottom on a diel basis and are classified as "polymictic." For seasonal stratification to develop, the lakes must be tens of meters deep or within craters. On the other hand, the very deep lakes, Malawi, Tanganyika, and Kivu, are meromictic, that is, they do not mix completely each year or for many years. Some of the small crater lakes are also meromictic, but due to their shallower depths, may mix during periods of drought which cause reductions in their depth and any chemical stratification.

Distance from the equator causes between lake variability in mixing dynamics for lakes of similar size and depth. Variability in solar radiation and in maximum and minimum air temperatures increases with distance from the equator. In addition, seasonality is influenced by the movement of the Intertropical Convergence Zone (ITCZ). Rainy seasons occur when the ITCZ passes over a lake, although there may be lags, with tropical lakes farthest from the equator having one rainy season and those closer having two, one as it moves north and a second as it moves south. The movement of the ITCZ determines the attributes of air masses which are advected over the lakes. For instance, when the ITCZ is over a lake, the air may be humid. As it moves north in the southern hemisphere or south in the northern hemisphere, cool dry air sweeps across the lakes and wind speeds tend to be higher. The deeper lakes tend to stratify during the rainy season and mixing is deepest during the dry seasons. Due to this suite of factors, the variability in lake surface temperatures increases with distance from the equator and the potential for seasonal stratification further increases.

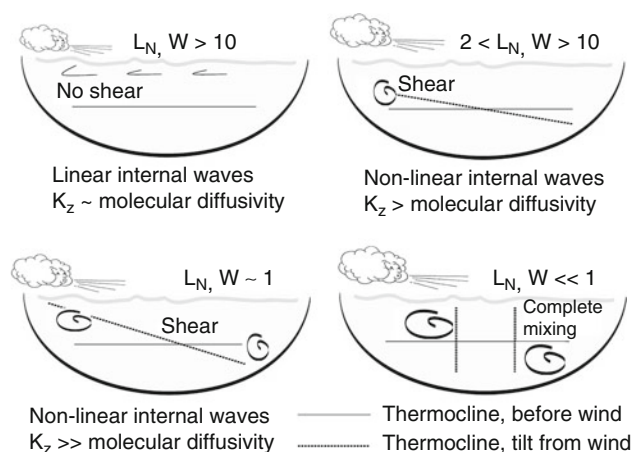
In the following, the first section reviews drivers of vertical mixing and processes which cause horizontal circulation. This section is followed by a description of the mixing dynamics in shallow, moderately deep, and deep tropical lakes and of unusual mixing dynamics caused by stabilizing inflows of groundwaters enriched in dissolved gases. Reviews of studies of mixing dynamics of tropical lakes can be found in Beadle (1981); Talling and Lemoalle (1998); and Spigel and Coulter (1996).

Stratification and mixing of lakes

As background, this section provides a brief description of the various processes causing mixing and horizontal transport in lakes, the meteorological drivers for these processes, and dimensionless indices which enable patterns to be identified. Convection, induced by heat loss and wind, causes the upper mixed layer to mix and deepen. Convection leads to the well-known overturning of many temperate lakes in the fall and tropical lakes during dry,

windy periods and is an important determinant of the depth of the mixed layer when lakes are seasonally stratified. The associated turbulence affects the light climate of phytoplankton by circulating them in a light gradient, and nutrient supply and gas flux via entrainment of water from below the mixed layer. Convection can also induce horizontal exchanges in lakes by processes known as differential heating, cooling, or wind mixing. These processes can be important for exchanges between the littoral and pelagic zone in small, sheltered lakes as well as larger lakes. These flows are density-driven flows, with increased heating in shallow regions of a lake causing surface overflows, and increased cooling in shallow regions causing gravity currents which sink until they reach water of similar density, or the bottom, and then flow offshore (Monismith et al., 1990). A related process, in which near continuous heating occurs on one side of an embayment or lake, can cause horizontal convection cells which persist for extended periods. Recent observations and modeling indicate it causes lake-wide transports in Lake Tanganyika (Verburg et al., 2011). Convective processes are quantified based on the amount of heating or cooling at a lake's surface. Evaporation is a primary driver, although cloud-free skies and concomitant increases in net long wave radiation are also important. The extent of convective mixing or circulation depends on air and surface water temperature, wind, and relative humidity. Thus, mixing depths can be deep in tropical lakes with their warm surface water temperatures, and nocturnal cooling can be sufficient to trigger inshore-offshore exchange by gravity currents. River inflows can be warmer or cooler than the receiving lake waters and initially flow over a lake's surface or penetrate below the surface, with the subsequent within-lake-mixing processes determining the extent of mixture of river and lake waters. The differences in molecular diffusivity of heat and salts can also cause vertical exchange and sometimes horizontal convective cells in lakes in which both temperature and conductivity increase with depth. This process is called "double diffusive convection" and is found in deep, chemically stratified lakes.

Upwelling of the thermocline and the breaking of nonlinear internal waves are induced by wind and are critical for vertical exchanges in stratified water bodies. Turbulence, generated by internal waves, promotes fluxes of solutes and particulates through the metalimnion, the stratified layer separating the warmer, weakly stratified upper mixed layer and the cooler, deeper waters or hypolimnion. Internal wave-mediated fluxes are particularly important for supporting the productivity of lakes during the periods of strongest stratification. The extent of thermocline tilting and nonlinear steepening and wave breaking can be predicted from two related dimensionless indices, the Wedderburn number (W) and its integral form, the Lake (L_N) number (Figure 1). $W = g/\rho (\Delta\rho h^2/u_{*w}^2 L)$ where g is gravity, ρ is density, $\Delta\rho$ is the density difference across the metalimnion, h is mixed layer depth, L is length of the lake, and u_{*w} is the friction velocity in the water and



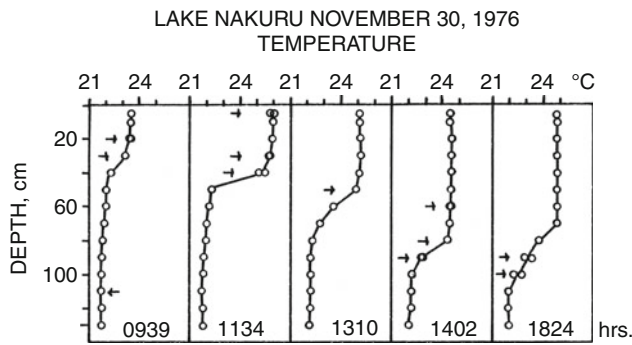
Stratification and Mixing in Tropical African Lakes,

Figure 1 Extent of tilting of the thermocline for different ranges of the Wedderburn (W) and related Lake numbers (L_N) and predicted changes in magnitude of the coefficient of eddy diffusivity, K_z , used to compute fluxes, $F = K_z \partial C / \partial z$ where C is concentration and z is depth. As W approaches 1, thermocline tilting increases and increasingly two-dimensional processes predominate and induce fluxes (Adapted from MacIntyre (2008)).

is derived from wind stress (Imberger and Patterson, 1989). Typically, u_{*w} is $\sim 0.001U$ where U is wind speed.

Shallow lakes: diel stratification and mixing

Diel stratification and mixing is one of the predominant attributes of shallow tropical African lakes. This pattern was first noted in Nyanza Gulf, Lake Victoria (Worthington, 1930). Lake temperatures are nearly isothermal in the morning, increase rapidly in the upper water column with morning heating, reach a maximum by early afternoon, and then decrease beginning late afternoon becoming isothermal at night with temperatures often similar to those at dawn on the previous day. Diel stratification has been subsequently noted in other African lakes, for example, Jebel Aulia Reservoir, Sudan (Talling, 1957); Lake George, Uganda (Ganf and Viner, 1973); Lake Nakuru, Kenya (Melack and Kilham, 1974); and Lake Kilotes, Ethiopia (Talling et al., 1973). These shallow lakes often have high attenuation coefficients (Secchi depths can be 25 cm) either due to high concentrations of phytoplankton or suspended sediments. Consequently, heat is rapidly trapped in near-surface waters, and due to the relatively large changes in density with small temperature changes in warm water, stratification is pronounced (Figure 2). In lakes with smaller attenuation coefficients, the diel stratification will not be as pronounced (Figure 3). Stratification dynamics can change from day to day if conditions are cloudy, as during rainy seasons, or if afternoons are windy. If winds increase when these lakes are strongly heating, surface currents are intensified and may cause internal waves to form with sufficient shear to cause vertical mixing. As solar radiation decreases,

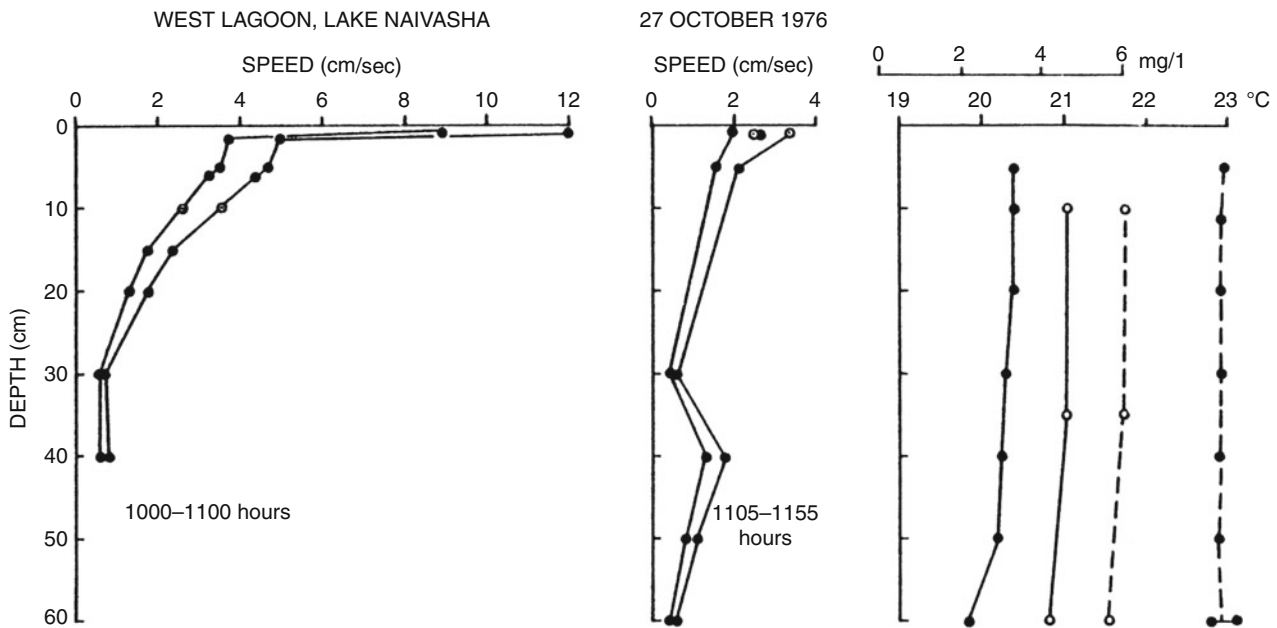


Stratification and Mixing in Tropical African Lakes,

Figure 2 Time series of temperatures in Lake Nakuru (42 km², maximum depth 3.3 m), Kenya, on November 30, 1976 illustrating morning heating and loss of heat and mixed layer deepening in response to cloud cover reducing solar insolation and gusty afternoon winds between 5 and 7 ms⁻¹. The Richardson number was 0.2 between 11 and 38 cm in the first profile suggesting sufficient shear within the diurnal thermocline to contribute to its deepening. Water was often anoxic below the diurnal thermocline and remained so until the mixed layer homogenized. Arrows indicate depths at which temperatures oscillated likely due to high-frequency internal waves. Duplicate open circles indicate range of temperatures at those times (From MacIntyre (1981)).

mixed layer deepening will be facilitated by increased evaporation and the resulting convective mixing. Time series observations in Lake Elementeita, Kenya, obtained over 13 months indicate a high degree of predictability in stratification dynamics in these shallow lakes (Melack, 2009). As a consequence of the stratification and the high productivity of many of the shallow African lakes, dissolved oxygen concentrations increase and decrease over diel cycles similar to temperature. Oxygen concentrations can reach 200% of saturation during the day. Interestingly, nocturnal cooling, which can induce isothermy, may not fully mix the dissolved gases at night.

Careful analysis is required to assess whether inshore-offshore exchanges are mediated by differential heating and cooling or by other processes (Okely et al., 2010). Time series observations in Pilkington Bay, an embayment in Lake Victoria, indicate that while the nearshore waters of inshore embayments often heat up more during the day than waters further offshore, conditions which could lead to buoyant overflows, wind-driven flows are more likely dominant during the day. Cooling at night can be sufficient to induce gravity currents that would enable exchange between inshore waters and larger channels (MacIntyre et al., 2002). During high winds, both the flows from surface currents and internal wave-induced flows may cause offshore waters to flush inshore channels.



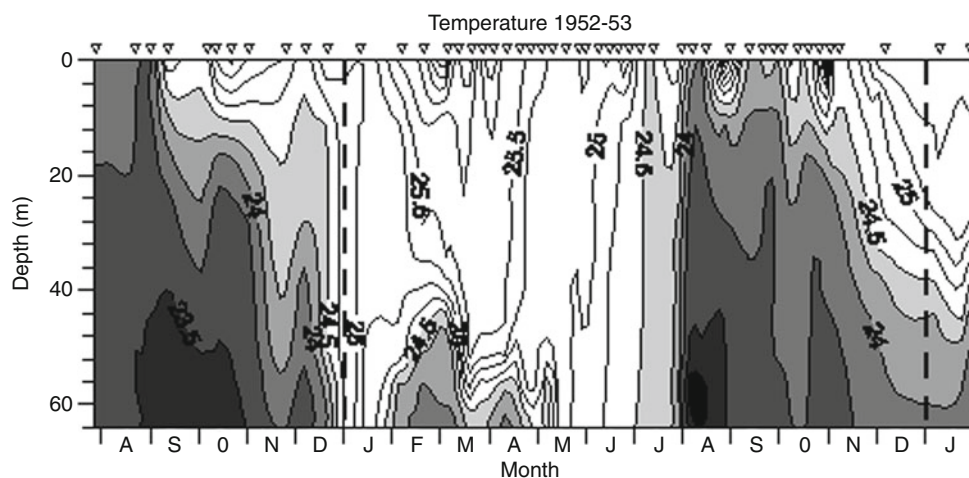
Stratification and Mixing in Tropical African Lakes, Figure 3 Vertical profiles of currents with a warm bead thermistor flowmeter and profiles of temperature (•) and oxygen (o) at 0930 h and 1,200 h on October 27, 1976 in a lagoon of Lake Naivasha, Kenya. Macrophytes were abundant and indicative of attenuation coefficients less than those in the main basin of the lake where $k_d = 1 \text{ m}^{-1}$. Temperatures increased 2.5°C in 3 h. Winds were light, below instrument threshold, 0.8 ms⁻¹, and up to 1.7 ms⁻¹, when the first velocity profiles were made and illustrate the high-near-surface speeds due to surface streaming. Winds averaged 1.2 ms⁻¹ during the second set of profiles. The upper most current measurements were 0.5–1 cm below the air-water interface in the first profile and 1.5 cm below the air-water interface in the second set of profiles (From MacIntyre (1984)).

Use of introduced or biological tracers can be used to infer dominant processes. Fish (1957), for instance, noted a large increase in the abundance of diatoms, originally only found inshore, in offshore waters after a strong wind event. Thus, while temperature differences between inshore and offshore waters may appear conducive for convective exchanges, the full suite of processes must be explored before definitive answers are obtained.

Moderately deep lakes: emergence of seasonality

Temperature differences are only 1–2°C between the surface and bottom waters of the moderately deep tropical lakes. Fish's (1957) time series measurements of temperature in 80-m-deep Lake Victoria indicated that seasonal stratification could develop despite such small temperature differences. His time series data (Figure 4), as well as that of Talling (1966), established that Lake Victoria is holomictic during the southeast monsoon, becomes weakly stratified over its entirety in the calmer, sunnier, and more humid period which follows, and that seasonal stratification develops beginning at the end of the short rains or start of the northeast monsoon in December. The stratification develops as winds in the day mix incoming heat downward forming a seasonal thermocline below 50 m. Thus, development of seasonal stratification takes about 3 months. Diurnal thermoclines remain a prevalent feature, with the depth of nocturnal mixing depending on the extent of nighttime cooling but to depths as great as

50 m during the long rains from February until April or May. Seasonal stratification persists, in general, until late May when cool, dry air masses and higher winds arrive with the onset of the southeast monsoon. The occasional holomixis to the north (e.g., during January in Figure 4), noted since the earliest time series measurements were made, was attributed to wind-induced downwelling of the thermocline. A cross-basin transect in May 1995 during high winds provided the first demonstration of the downwelling of the thermocline to the north and its upwelling to the south. Importantly, observations in other lakes have shown that on cessation of the wind, rocking of the thermocline can induce considerable mixing. Stratification to the north in Lake Victoria was considerably reduced after the event. The loss of seasonal stratification in Lake Victoria may be initiated by increased winds which cause the thermocline to upwell with concomitant mixing but ultimately results from the deep mixing due to heat loss. By June, heat losses, particularly to the south and west, increase threefold relative to other seasons, and, while diurnal thermoclines form in the upper 5 m, mixing at night can reach the bottom. Thus, while diurnal thermoclines form nearly every day in Lake Victoria, the depth of nocturnal mixing varies seasonally, with mixing of order 5–10 m in September, to depths up to 50 m from January through May, and to at least 60 m during the southeast monsoon. The mixing dynamics in Lake Victoria are intermediate to those in shallow lakes, where mixing goes to



Stratification and Mixing in Tropical African Lakes, Figure 4 Time depth diagram of isotherms (lines of constant temperature) for Lake Victoria (68,800 km², maximum depth 80 m), East Africa, 1952–1953, illustrating the well mixed conditions during the southeast monsoon (June, July), the development of weak stratification beginning in August with near-surface stratification due to heating, and stratification induced at depth likely due to flow of a gravity current. Temperature stratification at the beginning of December 1952 was 1.2°C. The buoyancy frequency, $N = g/\rho \, dp/dz$ where g is gravity, ρ is density, and z is depth, was 3.5 cycles per hour. While considered weak stratification by oceanic standards, such stratification is sufficient to support internal waves. For instance, at a deep ocean site near Hawaii where $N = 4$ cph, internal wave motions were 300 m crest to trough. The rising isotherms in October and December 1952 were accompanied by upwelling of water with low oxygen concentrations and are indicative of internal wave activity in the lake. The seasonal thermocline begins to develop in November–December and persists until May. Brief intervals of holomixis in January are likely due to downwelling of the seasonal thermocline during windstorms as indicated in Fig. 1 for Wedderburn numbers near 1 and provide further evidence for internal wave activity (Figure redrawn from Fish (1957)).

the bottom each night, and to those in the deeper African Great Lakes, where mixing during the dry season can reach to depths of 100–150 m.

Lake Albert in the Western Rift Valley is about 58-m deep and exposed to high winds during much of the year. Temperature differences are at most just over 1°C. With these conditions, seasonal stratification is even less likely than in Lake Victoria. Via a series of transects from inshore to offshore waters, Talling (1963) showed that differential cooling, and the gravity currents which result, was a likely cause of stratification deep in the water column during the short and long rains in this Great Lake. Differential cooling is facilitated in Lake Albert ($SA = 5,600 \text{ km}^2$, $z_{\text{mean}} = 25 \text{ m}$) by a shelf region to the southwest which is nearly 20-km long and less than 10-m deep. Thus, nocturnal cooling would typically extend to the bottom of the shelf and cause water temperatures to be cooler there than offshore. Silica and oxygen were strongly stratified below 35 m during the short rains – observations which indicate that even if temperature stratification is weak, pronounced gradients in solutes can develop. Talling hypothesized that horizontal convective processes would cause stratification in other tropical lakes, and there is evidence for it in Lakes Victoria and Malawi.

Deep lakes and the development of meromixis

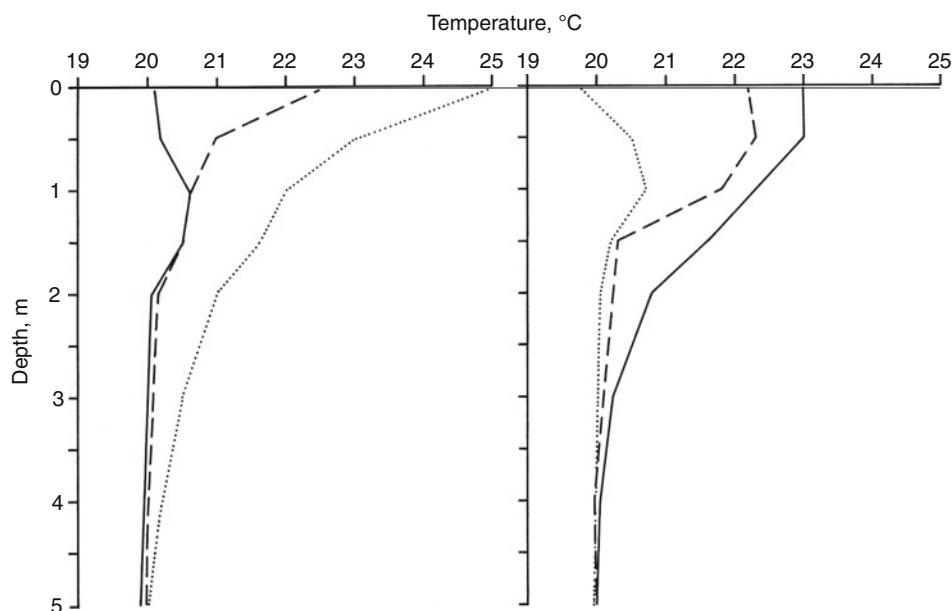
A defining characteristic of the deep African Great Lakes, Tanganyika, Malawi, and Kivu, is that they are meromictic and, at depths below 100 or 200 m, deoxygenated. That is, they do not fully circulate each year. Anoxia results from the decomposition of organic matter which has settled out of the mixed layer and from the lack of complete mixing which would reoxygenate the lower water column. The upper water column in these lakes undergoes diel stratification and mixing, a seasonal cycle of stratification and mixing dependent on solar insolation and on the movement of the Intertropical Convergence Zone, and associated changes in wind and air masses. Mixed layer deepening is greatest during the southeast monsoon with greater deepening to the south end of the lakes. For instance, mixed layer depths are up to 120 m at the south end of Lake Tanganyika (see Huttula and Sarvala, Figure 3, this volume). The lakes are meromictic because neither the heat losses nor the wind mixing are sufficient to cause mixing to the bottom.

Basin scale tilting of the thermocline during the southeast monsoon is another defining characteristic of these lakes. The upwelling of water from 100 m to the south was noted by Coulter (1963) for Lake Tanganyika, who also pointed out the importance of the upwelling for nutrient supply, primary productivity, and for sustaining the fisheries of the lakes. These detailed observations also indicated internal waves were present during other seasons. Later analysis, based in part on values of Wedderburn numbers less than 1 (Coulter and Spigel, 1991), indicated these would be nonlinear and thus capable of north-to-south transports. Heating rates are greater and heat losses are less to the north than the south of

Lake Tanganyika. Verburg et al. (2011) showed that a convective circulation forms in which warm water from the north is transported to the south in the upper mixed layer and cool water from the south flows north in the thermocline. This flow occurs early in the southeast monsoon (dry season) and persists for nearly 2 months after it ends and is responsible for a substantial redistribution of heat.

Crater lakes and chemically stratified lakes – Volcanic regions occur in mountainous areas in the Cameroon and in the East and West Rift Valleys. Due to phreatic explosions, that is, explosions resulting from magma superheating the groundwater, maar lakes form, with classic examples being Lakes Monoun and Nyos in the Cameroon, Lake Sonachi in Kenya, the crater lakes in Western Uganda, and the Bishoftu Crater lakes in Ethiopia. Many of these have unusual chemical composition. Diurnal heating and cooling occur in these lakes, but crater walls may limit the exposure of these lakes to wind forcing and the depth of mixing may be reduced relative to unsheltered lakes of similar depths (Figure 5). The study of seasonally stratified Lake Pawlo, one of the Bishoftu Crater lakes, was among the first to demonstrate that destratification and even holomixis occur in response to nocturnal cooling despite high solar radiation in the day (Wood et al., 1976). Shallow, closed basin, crater lakes may be meromictic due to freshening of surface waters during rain events and seepage of water with higher salt concentrations in the littoral and their subsequent flow as gravity currents to deeper depths in response to rain (MacIntyre and Melack, 1982). An example is Lake Sonachi, Kenya, whose depth varies from 5 to 8 m. Complete mixture may be possible after persistent droughts reduce the density differences between the upper and lower water column, but meromixis will be maintained if rainfall events are sufficiently frequent.

Lakes Monoun and Nyos, two maar lakes in the Cameroon, and Lake Kivu all share the distinction of having increased concentrations of carbon dioxide in their lower water columns, and due to the relatively recent explosions of Lakes Monoun and Nyos, have been called “killer lakes.” Lake Kivu additionally has elevated methane concentrations. The chemical stratification as well as the great depths of the lakes (Monoun 100 m; Nyos 210 m; Kivu 500 m) ensure that the lakes do not turnover seasonally and are thus meromictic. Due to the concomitant increases in temperature and conductivity, double diffusive convection has been observed in Lakes Nyos and Kivu (Schmid et al., 2004, 2010). If the concentrations of dissolved gases exceed a threshold set by hydrostatic pressure, they will come out of solution, and an explosive bubble plume will form. Lake Monoun last exploded in 1984 and Lake Nyos in 1986, and in the case of Lake Nyos, the gravity currents induced by the massive increase in carbon dioxide flowed into the valleys where people resided causing 1,800 deaths. To avoid future tragedies, pumping systems which vent CO_2 were installed in the two Cameroonian lakes in 2004 (Kling et al., 2005). Plans are being developed to similarly vent the gases in Lake Kivu, with a pilot plant



Stratification and Mixing in Tropical African Lakes, Figure 5 Temperature profiles illustrating diurnal heating and nocturnal cooling in 18 ha Lake Sonachi, Kenya, on 27–28 October 1973. *Left:* (—) 0700 Oct 27, (---) 1050 Oct 27, (···) 1320 Oct 27; *Right:* (—) 1645 Oct 27 (---) 1930 Oct 27, and (···) 0705 Oct 28. The lake is chemically stratified with crater walls 50–115 m above the lake. Two aspects of the stratification are unusual in this figure and likely result from the slight gradients in conductivity within the lake. Heating by 1,320 h 27 Oct occurs below 3 m, but the attenuation of photosynthetically available radiation was 3 m^{-1} which would restrict surface heating to depths above 2 m. Temperature profiles in other months indicated heating and cooling in the upper 2 m as would be expected and near isothermy near dawn. Wind speeds tended to be light in the crater, so vertical mixing was unlikely to have caused the increased heating below 2 m at 1,320 h. Instead, differential heating combined with spatial differences in conductivity likely induced gravity currents which transported heat below 3-m depth. Increased oxygen concentrations below 2 m on other sampling dates also suggest inshore-offshore exchange by gravity currents. The temperature inversions in early evening and in the morning are also unusual and likely persisted due to the weak chemical stratification (From MacIntyre (1981)).

in operation. The 1.2 million people living around Lake Kivu are currently at risk, so ventilation is urgent with the added benefit that the methane will be used to generate electricity and will promote development.

Changes in thermal structure due to changes in climate and land use – Temperatures throughout the water column have increased due to global warming in Lakes Tanganyika and Malawi (Verburg et al., 2003; O'Reilly et al., 2003; Vollmer et al., 2005) with the greatest increase in the upper water column. This increase in stratification has led to a reduced flux of nutrients into the upper water column of Lake Tanganyika and a reduction in the abundance of diatoms. Consequences of these changes for the fisheries in these lakes are not yet known. Hecky (1993) reported increased water temperatures and stability in Lake Victoria and an increase in the volume of anoxic water since Talling's measurements in 1966. The increased anoxia is a result of land use changes in the basin. Time series temperature data from 1994 to 1996 indicate interannual variability in the extent of warming. Whether increased stability, which will contribute to persistent anoxia, is a trend or whether it will vary likely depends on the many factors influencing East African climate. For example, rainfall in the Lake Victoria region

varies with phase of the El Nino-Southern Oscillation and of the Indian Ocean Dipole (Nicholson and Yin, 2002; Williams and Funk, 2010). Wind records based on reanalysis of satellite data and land-based data from 1948 through 2010 indicate conditions were windier in the early 1950s and 1960s than in the mid-1990s. Winds were again high near 2000. Thus, temperatures and mixing dynamics in moderately deep tropical lakes may show considerable year-to-year variability. Winds over the tropical African lakes are sensitive to changes in sea surface temperature and upwelling in the Atlantic, Pacific, and Indian Oceans. While increased air temperatures may predominate due to global warming, the other factors which affect mixing dynamics will remain variable.

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Cross-references

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[Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology](#)
[Thermal Regime of Lakes](#)
[Victoria Lake](#)

STRATIFICATION IN LAKES

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Synonyms

Layered structure of lakes; Non-mixed lakes

Definition

Stratification is defined as the development of relatively stable light and warm layers above colder deeper layers within a body of water. Thermal stratification is related

to water density and is effected by incoming heat, water depth, and the degree of water-column mixing.

Introduction

Lakes receive thermal energy mainly through the lake surface. Part of the shortwave energy from the sun penetrates through the surface and is absorbed in the near-surface layers. In a typical lake this happens within the uppermost 10 m, but in very clear water lakes this penetration can reach down to tens of meters. Long-wave energy from clouds and the atmosphere is absorbed within the first centimeters in the lake water body. Thermal energy is also exchanged between the lake bottom and the lake water body, but normally it has only a secondary role in lake thermodynamics.

Accumulation of thermal energy in the near-surface layers will move the center of gravity of the lake upward and thus the potential energy of the lake water body is increased. Moving it downward and mixing the lake water vertically requires mechanical energy, which is supplied by the wind.

Water temperature determines the density in freshwater lakes. The density maximum at 3.98°C water temperature has a fundamental effect on the development and destruction of the lake stratification.

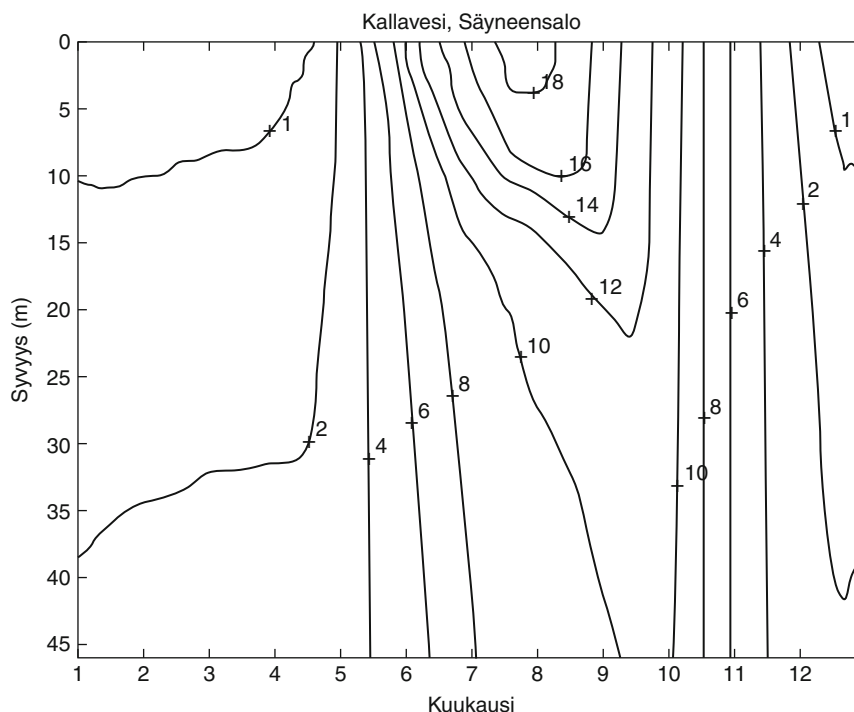
Stratification has many ecological consequences. During the stratified period, the metalimnion effectively prevents water-column mixing, isolating the hypolimnion from gas exchanges with the atmosphere. In

addition, the hypolimnion is often too poorly lit for photosynthetic production of oxygen by green plants. Without an influx of oxygen, the hypolimnion can become depleted of oxygen during the summer stratified period due to oxygen use by bacterial decomposition of organic matter.

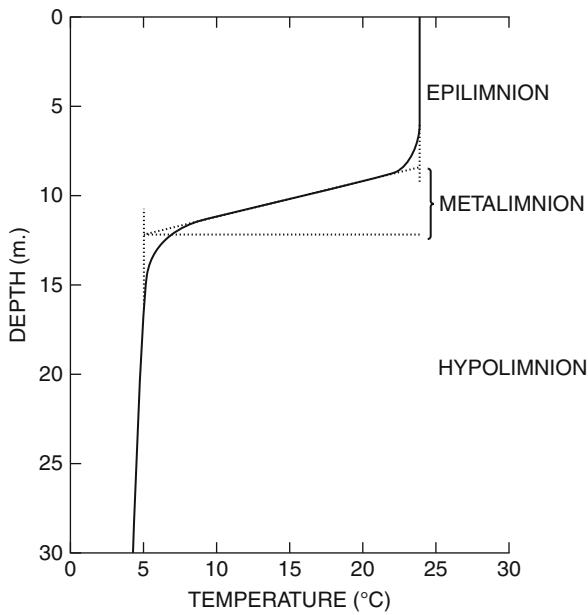
Annual cycle of lake water temperature

The annual cycle of lake water temperatures in temperate lakes is typically as follows. In spring during ice melting, or even during the snow-free period before the ice melting, an overturn, a complete vertical mixing, of the lake water body happens (Figure 1). Another overturn happens in autumn, when the surface waters have been cooled so that they are lighter than the deep waters. The length of the autumn overturn is very much dependent on the autumn weather and is anyway longer than the spring overturn. The overturn is important to the vertical exchange and renewal of deep abyssal waters, their oxygen enrichment, and the life in them.

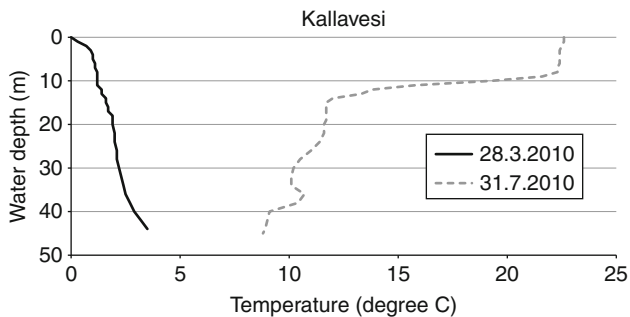
In summer most of the lakes in the temperate climatic zone are stratified. The almost homothermal surface layer extending down to 5–20 m is called the epilimnion (Figure 2). Under it is the metalimnion, where the water temperature decreases rapidly. The plane with maximum decrease is called the thermocline. The metalimnion is usually some meters thick. Under this is a cool layer with an almost homothermal structure which is called the hypolimnion.



Stratification in Lakes, Figure 1 The annual mean course of water temperature during the period 1981–2000 as isotherms in Lake Kallavesi, Finland, at the Säyneensalo (From Korhonen, 2002).



Stratification in Lakes, Figure 2 Typical thermal stratification of a lake into epilimnetic, metalimnetic, and hypolimnetic water strata. Dashed lines indicate planes for determining the approximate boundaries of the metalimnion (From Wetzel, 2001).



Stratification in Lakes, Figure 3 Two water temperature profiles in Lake Kallavesi, Finland. One from late winter, when the lake was still ice covered, and one from the period of strong stratification.

In winter waters just underneath the ice have a temperature near 0°C. The deep abyssal waters have a temperature somewhat below the temperature of maximum density (Figure 3).

The temperature in small humic lakes can rise as the oxygenation of organic compounds produces small amounts of heat. Also in some lakes heat released from sediments and convective accumulation of heated waters to the abyssal areas is seen as a temperature increase of deep waters.

Besides the seasonal temperature and stratification variation, diurnal variations are also found in the lake water

body. This happens especially during calm cloudless summer days and nights. The solar radiation heats up the surface waters increasing daytime stratification with some extra layers in the epilimnion. Nocturnal cooling of air leads to strong sensible heat loss from the lake surface, which is also emitting heat by long-wave radiation. The cooled waters sink down and cause vertical mixing and this leads to the homothermy of the epilimnion.

Lake classification based on thermal stratification

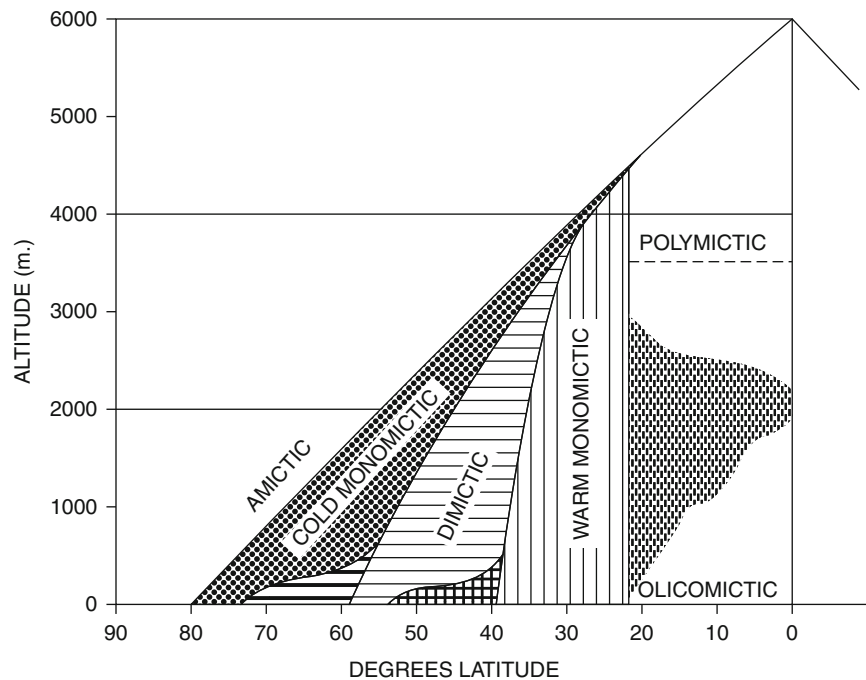
The stratification variation as presented above is typical in the temperate climatic zone, where lakes are most abundant. A lake presenting this type of stratification is called dimictic. A lake classification system based on stratification and circulation patterns has been introduced by Hutchinson and Löffler (1956) and Hutchinson (1957). Monomictic lakes have one turnover period in a year. Cold monomictic lakes are situated in the arctic zone with water temperatures never rising above 4°C. Warm monomictic lakes are situated in the subtropics with water temperatures never cooling down to 4°C. Oligomictic lakes face turnover very seldom. It can happen, for example, in stormy periods. Polymictic lakes face the turnover several times in a year. Cold polymictic lakes circulate continually at temperatures near or slightly above 4°C. A warm polymictic lake is usually a tropical lake that exhibits frequent periods of circulation at temperatures above 4°C. A cold amictic lake never has a turnover as it has a perennial ice cover. In meromictic lakes vertical mixing happens in the epilimnion and metalimnion but hypolimnetic waters are amictic. Typically deep tropical lakes, like Lake Tanganyika, are meromictic. The relationships of thermal lake types with altitude and latitude are presented in Figure 4.

Lake water stability

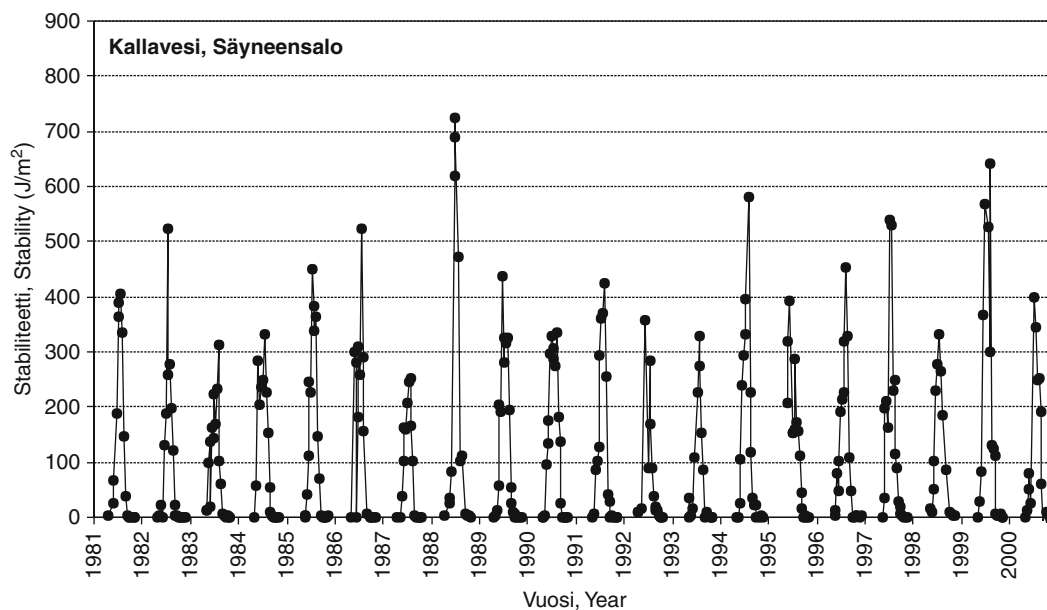
Stability (S) per unit area of a lake is the quantity of work or mechanical energy in Jm^{-2} required to mix the entire volume of water to a uniform temperature without heat exchange with the environment (Birge, 1916; Schmidt, 1928). During summer stratification, stability expresses the amount of work needed to prevent the lake from developing a thermal stratification. Thus stability quantifies the resistance of the prevailing stratification to disruption power by the wind. In a particular lake it varies during the course of the summer and from year to year (Figure 5).

Effects of global warming on lake stratification

The effect of global warming on lakes in the temperate zone has been studied actively during the recent decades (Kuusisto, 1989; Huttula et al., 1992; Elo et al., 1998). The main method has been mathematical modeling. Future scenarios in both shortwave and long-wave heat balance components of the lake surface are available in the models. The lack of wind scenarios weakens the lake modeling results and most of the lake simulations have been made with present winds. It seems, however, that the increase of air temperature leads to earlier melting of



Stratification in Lakes, Figure 4 Schematic arrangement of thermal lake types with latitude and altitude. The areas with no label (horizontal and crossed bars) present transitional regions. Likewise the broken vertical bars between oligomictic and polymictic lakes present regions of mixed types, mainly warm monomictic lakes (From Wetzel, 2001).



Stratification in Lakes, Figure 5 Stability of the representative area in Kallavesi during the period 1981–2000 (From Korhonen, 2002).

snow from the lake ice surface and earlier ice cover melting than in present climate. This will happen 1–2 months earlier than at present (Huttula et al., 1992; Elo et al., 1998). The formation of ice cover will happen a few weeks later than at present and in large lakes ice-free winters will

become more frequent than at present. The surface temperature increase in summer will follow the temperature increase of the air. The fate of thermal stratification depends on the changes of the wind by large. It seems that in deep large lakes the epilimnion will deepen from present and

may even change some dimictic lakes to polymictic lakes. Also some sheltered lakes may face turnover also in spring instead of in autumn. They presently start to stratify already with the ice cover on (Saura et al., 1996).

Summary and conclusions

The special density distribution due to water temperature leads to thermal stratification in lakes, where a relatively stable, warm layer is found near the surface and colder layers in deep waters. In between there is a layer with a rapid water temperature decrease. It is called the metalimnion. In wintertime, inverse stratification is found. There the coldest and lightest waters are found near the surface and the warmest waters approaching the temperature of maximum density are in the deep layers. Many versions of this basic system are found depending on the lake's latitude, altitude, and wind forcing on the lake. The stratification of lakes has many ecological consequences. Global warming will change the lake stratification, basically by increasing the surface layer temperature and extending the open water period in lakes in the temperate zone.

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SUBMERGED VEGETATION IN SHALLOW LAKES

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Synonyms

Hydrophytes s.str; Submerged (submersed) macrophytes;
 Submerged (submersed) plants

Definition

Submerged plants. Plants in which the shoots and leaves are totally restricted to the water column. Inorganic carbon is either taken from the water or the sediment. Flowers may stretch above the water surface. The plants can be rooted or free-floating and belong to the vascular plants, mosses (bryophytes), stoneworts (Characeae) and macroalgae.

Introduction

A distinct zonation of plants can be observed across the lake shoreline: Below different types of terrestrial vegetation only occasionally affected by flooding, reedbelts with different species of emergent plants dominate on water-saturated and submersed soils down to a depth of about 1.5 m. Outside the reedbelts, floating-leaved plants can occur at water depths from around 0.5–3 m, but lack in wind-exposed areas. While these two plant life-forms are spreading across the water-atmosphere interface and assimilate atmospheric carbon dioxide during photosynthesis, submerged plants, which occur at all depths, are mainly restricted to the submersed environment (Wetzel, 2001).

Adaptations to the submersed environment among submerged plants

Compared to the terrestrial situation, the submersed environment offers specific conditions, which submerged plants respond to by both morphological and physiological adaptations. Drought adaptations such as thick cuticles (see exception below: isoetids) and leaves covered by hairs are lacking among submerged plants, and in most groups, root biomass is rather low. Due to high buoyancy within the water column, supporting tissues are reduced, lignin is generally lacking in submerged plants, and cellulose content is low. Nutrients such as nitrogen and phosphorus can be taken up both from sediment and water column. Finely dissected leaves are common among submerged plants and facilitate the uptake of these nutrients as well as inorganic carbon (see below) (Wetzel, 2001).

Solar insolation reaching the water surface is partly reflected, and only part of this light is entering the water column. On its way down, this light decreases due to

absorption by dissolved substances (water color) and scattering by particulate material (both organic and inorganic). The attenuation (vertical decrease of light through the water column) varies substantially among lake types, but generally, the submersed environment can be characterized as a low-light habitat (Scheffer, 1998; Wetzel, 2001). In submerged plants, chloroplasts are often situated in the epidermis of the rather simply structured leaves. Physiologically, low light compensation point and low light saturation point as well as low maximum photosynthesis rate characterize submerged plants as typical shade-adapted plants (Pott and Remy, 2000; Wetzel, 2001).

One of the main factors limiting primary producers in the submersed environment is carbon availability. Submerged plants have developed different mechanisms for carbon acquisition (see below). Like other aquatic plants, submerged vegetation has to cope with anaerobic conditions within the sediments. Gas transport from the leaves down to the roots and rhizomes facilitated by extensive aerenchymas is one mechanism of adaptation to anaerobic soils. Another main mechanism is physiological adaptations to different toxic substances typical in anaerobic soils (Wetzel, 2001).

Several submerged macrophytes like *Zannichellia* spp., *Vallisneria* spp., and *Ruppia* spp. are hydrophilous, i.e., the pollen is spread by the water. More common is wind pollination (anemophily) which occurs in species that develop flowers above the water surface (*Myriophyllum* spp., *Potamogeton* spp.). A third mechanism of pollen dispersal is insect pollination (entomophily), which occurs in *Utricularia* spp. and other submerged macrophytes.

Water is the most common transport vector for seed dispersal in submerged macrophytes. To colonize remote lakes and reservoirs, transport by animals is common, especially transport of seeds and oospores within the intestine system of waterfowl.

Apart from this sexual reproduction, vegetative propagules are commonly formed in submerged macrophytes, many of which serving as specified hibernacles like condensed shoots (turions) in *Utricularia* and *Myriophyllum* or belowground tubers in *Stuckenia pectinata* (former *Potamogeton pectinatus*) (Pott and Remy, 2000).

Different growth forms of submerged macrophytes

Among submerged plants, angiosperms are represented by different growth forms (Figure 1). Isoetids are typical for softwater lakes with low or moderate nutrient concentrations and clear water. This bottom-dwelling life-form is represented by a number of species such as *Isoetes* spp. (Pteridophyta: Isoetaceae), *Littorella uniflora* (Plantaginaceae), *Lobelia dortmanna* (Lobeliaceae), and *Subularia aquatica* (Brassicaceae). In spite of their belonging to taxonomic groups rather distant from each other, all species are morphologically similar in a way that it is sometimes hard to distinguish them from each other. Common characters are a rosette growth form and short leaves, high ratio of root/shoot biomass, extended

aerenchymas, and a thick cuticle (Pott and Remy, 2000; Wetzel, 2001).

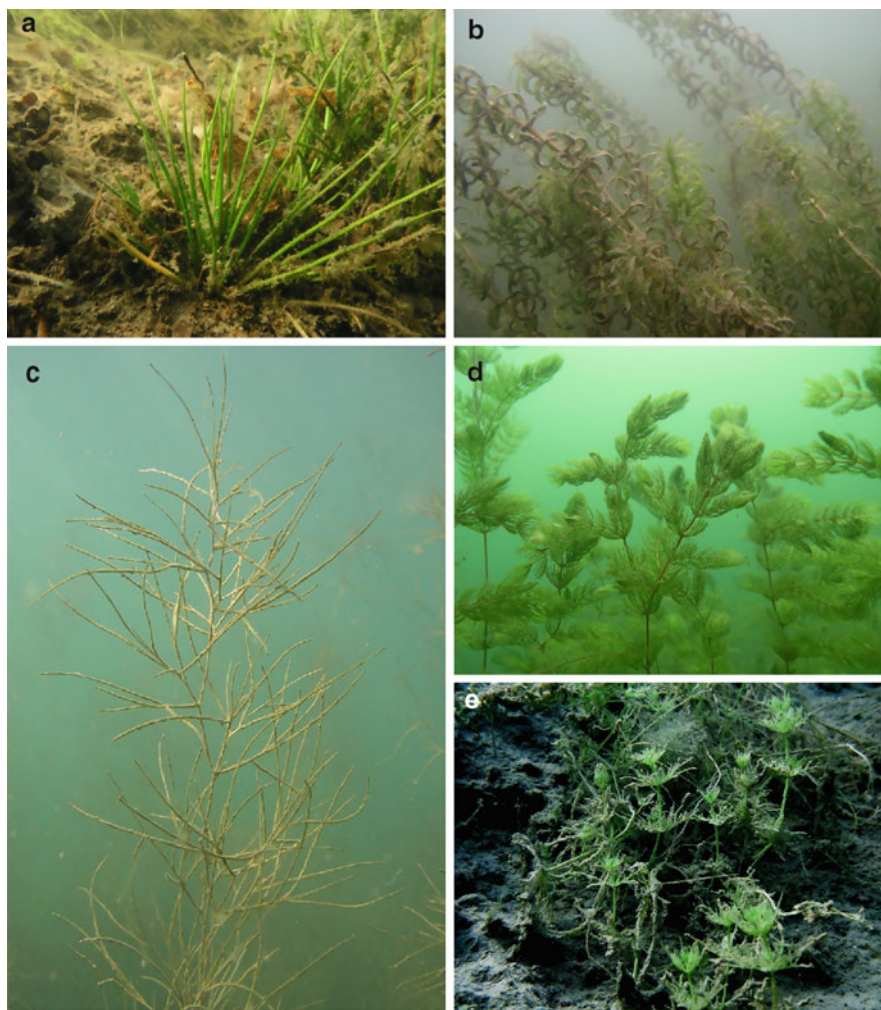
Apart from isoetids (see above), submerged angiosperms are taller and often characterized by more or less finely dissected leaves. Among this elodeid growth form, many species are erect (e.g., *Elodea*) forming long shoots in the water column. Other species have a canopy-like growth form (e.g., *Stuckenia pectinatus*) in which the shoots divide first in their upper parts. This growth form mainly occurs in nutrient-rich, turbid water. A few elodeid angiosperm species are non-rooted (e.g., *Ceratophyllum*).

Stoneworts occur in different lake types. While softwater lakes are mainly inhabited by different *Nitella* species and only few species belonging to the genus *Chara*, *Nitellopsis obtusa* and most species of the genus *Chara* mainly occur in nutrient-poor hardwater lakes where they can form dense mats and dominate the submerged vegetation (Wetzel, 2001; Figure 2). Characeae are macroalgae belonging to the division Streptophyta. They are bottom-dwelling plants forming branched thalli attached to the sediments by thin, thread-like rhizoids.

Submerged plants and eutrophication

With increasing nutrient loading, a dominance shift occurs among primary producers in shallow lakes. Free-floating microalgae (phytoplankton) as well as attached microalgae (periphyton) which only can take up nutrients from the water column are favored by this nutrient increase. Submerged plants, which can take up nutrients also from the sediments, suffer from increasing shading by both periphyton and phytoplankton and decrease drastically at a certain critical nutrient loading (Phillips et al., 1978). Internal feedback mechanisms explain this sudden shift (see chapter *Alternative Stable States in Shallow Lakes*).

Among submerged plants, bottom-dwelling growth forms (isoetids and stoneworts) depend on high light availability at the sediment surface (van den Berg et al., 1998). This life-form is therefore most sensible to higher turbidity during increasing nutrient loading and often disappears from eutrophied lakes (Wetzel, 2001) or is restricted to very shallow water (Blindow, 1992). Both isoetids and charophytes are therefore used as bioindicators for high water quality (Schneider and Melzer, 2003; Søndergaard et al., 2010). In erect and canopy-producing angiosperms, rapid shoot elongation is common at poor light availability (Barko and Smart, 1981). Canopy-producing plants concentrate the major part of their biomass close to the water surface where light availability is at its maximum (Titus and Adams, 1979). Large hibernacles enable a high initial growth rate during spring even under turbid conditions (Titus and Adams, 1979; Moen and Cohen, 1989). In shallow, turbid lakes, canopy-producing plants like *Stuckenia pectinatus* can grow down to about 1 m depth independently of turbidity (Blindow, 1992; Scheffer et al., 1992).



Submerged Vegetation in Shallow Lakes, Figure 1 Different growth forms of submerged plants. (a) Isoetids (bottom-dwelling): *Isoetes lacustris* (b) Elodeids – erect form: *Elodea nuttallii* (c) Elodeids – canopy-producing form: *Stuckenia pectinata* (d) Elodeids – free-floating form: *Ceratophyllum demersum* (e) Stoneworts (bottom-dwelling): *Chara vulgaris* (Photos: Klaus van de Weyer).

Submerged plants and carbon assimilation

In the submersed environment, dissolved carbon dioxide (carbonic acid) is in continuous exchange with atmospheric carbon dioxide. When carbon dioxide is produced or consumed within the water column by processes like photosynthesis or respiration, the equilibrium between air and water is restored by diffusion. This is a rather slow process, however, causing deficiency in inorganic carbon when aquatic photosynthesis is rapid.

Dissolved carbon dioxide (CO_2) forms a chemical equilibrium with bicarbonate (HCO_3^-) which in turn is in equilibrium with carbonate (CO_3^{2-}). These equilibria are pH-dependent: Only in acid and subneutral water, carbon dioxide is the main form of inorganic carbon, while bicarbonate dominates in neutral to slightly alkaline water and carbonate in highly alkaline water (Wetzel,

2001). In hardwater lakes, calcium carbonate (CaCO_3) is precipitated and forms an additional pool of inorganic carbon.

For submerged plants, inorganic carbon is a critical limiting factor. Carbon dioxide is the preferred form of inorganic carbon and easily taken up by all species. In softwater lakes, the inorganic carbon is therefore easily available, but the total pool is rather limited. In hardwater lakes, which are characterized by slightly alkaline conditions, the dissolved pool is replenished from the insoluble CaCO_3 pool upon consumption. In these lakes, the total amount of inorganic carbon is far higher, but dominated by bicarbonate which is not easily available for assimilation.

While some submerged plants are restricted to uptake of dissolved carbon dioxide (e.g., water mosses), most



Submerged Vegetation in Shallow Lakes, Figure 2 Dense mats of the stonewort *Chara rudis* in a calcium-rich alpine lake in southern Germany (Photo: Klaus van de Weyer).

species have evolved specific strategies for carbon assimilation (Madsen and Sand-Jensen, 1991). Carbon storage at night (CAM metabolism) is common among isoetids (Keeley, 1998). Plants belonging to this group are also able to take up carbon dioxide from the sediments. The specific morphology of this life-form (see above) facilitates the upward transport of carbon dioxide to the chloroplasts. Other species (e.g., *Myriophyllum* spp., *Potamogeton* spp.) develop aerial leaves which allow access to the atmospheric pool of carbon dioxide. By far the most important adaptation of carbon uptake and widespread among submerged angiosperms and stoneworts is bicarbonate assimilation. Different mechanisms have been proposed for bicarbonate uptake, each involving active, ATPase-mediated proton fluxes across the cell boundaries. (Madsen and Sand-Jensen, 1991; Ray et al., 2003).

Submerged vegetation in different lake types

The different adaptations to light and carbon limitation among submerged plants explain the restriction of different life-forms to specific lake types.

CAM metabolism and uptake of carbon dioxide from the lake sediments give isoetids a competitive advantage under the conditions of low carbon availability in softwater lakes. Significant use of sediment CO_2 has not been found in erect and canopy-producing angiosperms possibly due to long transport paths and low root biomass (Madsen and Sand-Jensen, 1991). Eutrophication of softwater lakes not only causes an increase in plant nutrient concentrations like nitrogen and phosphorus but is also accompanied by an increase of the lake's buffer capacity

and carbon pool. Erect and canopy-forming angiosperms gain advantage under increased availability of inorganic carbon in the water column and outcompete the bottom-dwelling isoetids (Spierenburg et al., 2009).

Oligotrophic hardwater lakes are often dominated by stoneworts. Bicarbonate is strongly withdrawn above dense beds of stoneworts probably due to both uptake and precipitation of CaCO_3 (van den Berg et al., 1998). As *Chara* species use bicarbonate efficiently and have high growth rates even at low levels of inorganic carbon (van den Berg et al., 2002), they may have a competitive advantage under these conditions. Also in this lake type, however, erect and canopy-producing angiosperms dominate under high nutrient concentrations as they can shade and outcompete the bottom-dwelling stoneworts (Moen and Cohen, 1989).

Interactions between submerged plants and microalgae

Free-floating and attached microalgae (epiphyton) are favored by increasing nutrient concentrations in the water column and affect submerged macrophytes negatively mainly by shading (see above). Interactions between epiphyton and its plant substrates are common and complex and include, but are not restricted to competition for nutrients and carbon (Wetzel, 2001). Different toxic substances have been isolated from a number of submerged plants. Apart from their possible function as protection against herbivory, these substances often inhibit microalgae. Such allelopathic interactions are probably common within the submerged vegetation (Gross, 2003).

Submerged plants in the trophic web

In shallow lakes, submerged vegetation can form substantial biomass. In such lakes, submerged plants act as a key factor having substantial impact on all levels of the trophic web. Apart from offering food to waterfowl and fish, the vegetation offers food and protection for zooplankton, macroinvertebrates, and small fish; accumulates nutrients; reduces sediment resuspension; and determines the structure of the microbial community (see single chapters in Jeppesen et al., 1998). Due to its positive effect on water clarity, (re)establishment of submerged vegetation is one of the major goals during biomanipulation (see chapters [Lake Restoration](#) and [Alternative Stable States in Shallow Lakes](#)).

Summary

In submerged plants, shoots and leaves are situated within the water columns. The plants are adapted to life below the water surface by a number of morphological (e.g., reduced supporting tissues, finely dissected leaves) and physiological adaptations (shade adaptation in photosynthesis). One of the most important factors limiting photosynthesis is assimilation of inorganic carbon which is taken up either as free carbon dioxide or bicarbonate from the water phase. In isoetids, a life-form with rosette leaves typical for softwater lakes, sediments serve as source for carbon dioxide. Ground-dwelling plants like isoetids and stone-worts are sensitive against eutrophication because of light limitation, while erect elodeids and especially canopy-forming species are more tolerant.

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Cross-references

[Alternative Stable States in Shallow Lakes](#)
[Aquatic Plants](#)
[Nutrient Balance, Light, and Primary Production](#)
[Sedimentation Processes in Lakes](#)

SURFACE SEICHES

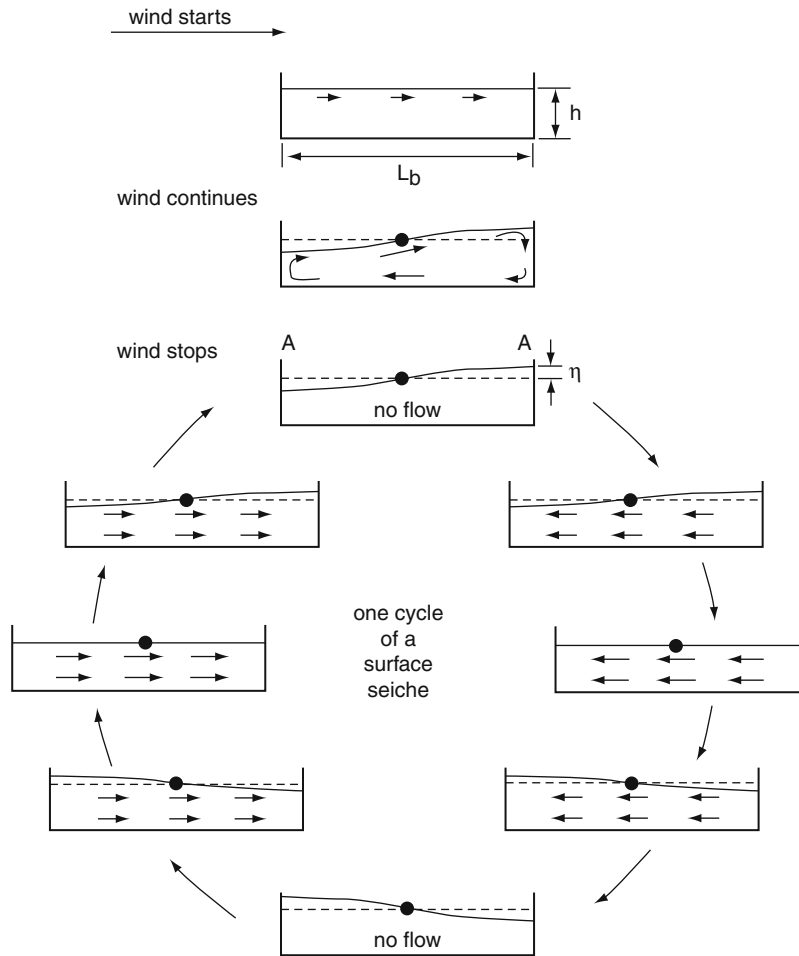
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Definition

A seiche is a standing surface wave in an enclosed or partially enclosed body of water.

In a lake, a surface seiche is most often produced when wind that has created a storm surge at the end of the lake suddenly ceases ([Figure 1](#)). Due to the restoring force of gravity, the lake surface first goes back to the still water level, and then, due to the inertia of the system, it overshoots and continues to oscillate around the nodal point in the center of the lake ([Figure 1](#)). The nodal point experiences no vertical motion. Maximum amplitudes occur at antinodes at the basin ends. Detailed observations of this



Surface Seiches, Figure 1 Definition sketch for a uninodal surface seiche in a rectangular basin. *Black dot*: nodal point, *A*: antinodes, *dashed line*: still water reference surface level, and *arrows*: mean orientation of water mass movement.

surface oscillation were made in Lake Geneva by Forel (1895) who used the term “seiche” to describe this motion. Seiche motion slowly decays under the influence of friction, and a decay rate of about 3% for each seiche period has been estimated for Lake Geneva.

This movement can be approximated by a standing wave with a wavelength L that is twice the basin length L_b (Figure 1). If $h/L_b < 0.2$, which is the case in most lakes, shallow water wave conditions apply. Starting from the depth-integrated mass transport equations, an equation for the period of surface seiches can be obtained from the resulting equation for the surface elevation η .

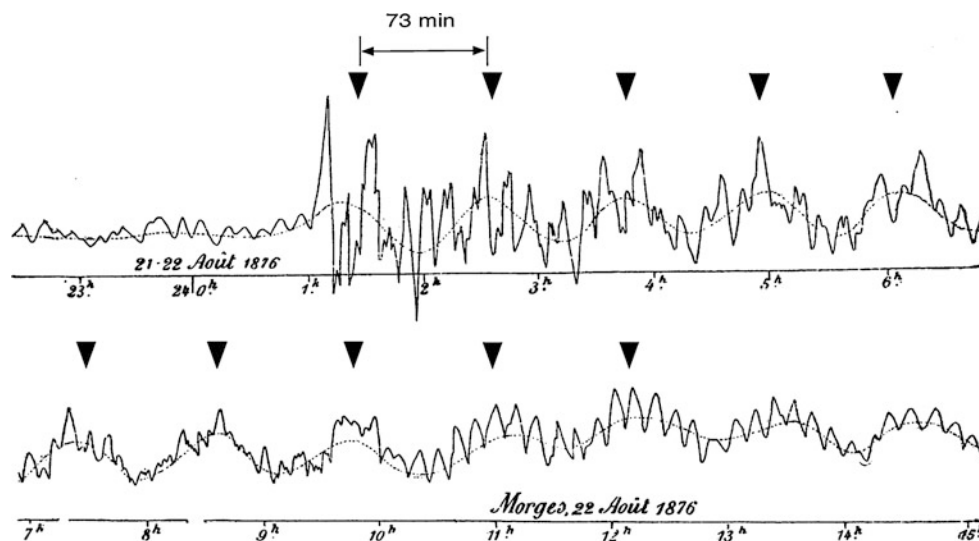
$$\frac{\partial^2 \eta}{\partial t^2} - c^2 \frac{\partial^2 \eta}{\partial y^2} = 0$$

This is a simple 1D wave equation. One can find a wave solution for this equation by taking the storm surge solution and adding a series of stationary waves that satisfy

the initial conditions. The resulting seiche period has the following form:

$$P = \frac{2L_b}{n\sqrt{gh}}$$

This equation is known as the Merian equation. The period of the oscillation is determined by the geometry of the basin. For lakes of a given length L_b , the mean depth will modify the period inversely. The number of nodes n determines the order of the surface oscillation. The period of the fundamental seiche mode (uninodal) is given by $n = 1$. It was found that this equation also provides good estimates for real basins, as long as they have a fairly regular shape. The periods of seiches in lakes typically fall into the range of minutes (e.g., the period of the fundamental seiche in “Lake Geneva” is about 73 min, Figure 2). For higher harmonics, $n > 1$, deviations in the observed period from the above equation may occur due to the



Surface Seiches, Figure 2 Recording of surface seiches in Lake Geneva (at Morges, Switzerland). Two different seiche oscillations are superimposed in this recording: the seiche along the long axis of the lake with a period of 73 min (marked by eye by full triangles) and a transversal seiche with a period of about 10 min. Note that the transversal seiche slightly changes periods over time due to the irregular shape of the basin (Modified after Forel, 1895).

irregular shape of a lake basin. If the basin is open at one end, such as in a harbor or a bay, the connecting line to the open lake has to be a node. The corresponding period for the lowest order seiche is twice that of the lowest order seiche that would exist, if the basin were closed.

A seiche is a surface wave and, thus, generates shallow-water wave-type movement within the lake which periodically varies in time and space (Figure 1). Over the period of a seiche, the lake system oscillates twice between a maximum of potential energy (no flow, Figure 1) and a maximum of kinetic energy (Figure 1, flat surface). Typical seiche amplitudes may range from a few centimeters in small to medium sized lakes to tens of centimeters in large lakes. The resultant seiche currents are smaller than other types of lake currents. The period and the currents of a seiche in a lake basin of irregular shape can be analyzed by a numerical model proposed by Defant (1918).

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Cross-references

[Basin-Scale Internal Waves](#)
[Circulation Processes in Lakes](#)
[Geneva Lake](#)
[Internal Seiches](#)
[Mixing in Lakes](#)

SUSPENDED SEDIMENT CONCENTRATION IN STRATIFIED LAKES ESTIMATED BY ACOUSTIC METHODS

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Introduction

A wide variety of techniques have been used to measure sediment concentration in rivers, such as conventional samplers, optical method instruments, and acoustic instruments. Acoustic Doppler current profilers (ADCP) and velocimeters (ADV), while their primary use is for velocity measurements, also provide information about the quantity and type of particulate matter in the water. Recent research has been on the use of acoustic methods to measure suspended sediment concentration (SSC), since an acoustic instrument can replace conventional turbidity meters and provide information about velocity, temperature of water, and sediment concentration time series simultaneously.

Using acoustic instruments for SSC measurements in water bodies has many advantages. These advantages include simultaneous measurements and description of the whole water column and sediment suspension structure. Furthermore, ADCPs can be used from a moving boat, eliminating the need to anchor the boat. When an acoustic instrument is calibrated for a water system, no additional sensor is needed to measure SSC, which enables the researchers the simultaneous measurements of velocity and concentration required for most sediment transport studies. Also, turbidity-measuring instruments use optical methods which have limitations for biological fouling. In spite of the advantages, the primary barrier to the development of a comprehensive sediment concentration prediction methodology by acoustic methods has been the lack of sufficient coupled observations of turbidity and acoustic Doppler velocity measurements to develop such a relation. One of the limitations of using acoustic instruments for SSC predictions is that they measure the velocity of acoustic targets (e.g., solid particles) rather than the fluid velocity where the sediment and fluid are assumed to travel at the same velocity. This assumption is likely to be valid only when considering fine sediments dominantly in suspension. For coarser particles (e.g., sand), this effect may introduce additional uncertainty. Another limitation is that, as the sediment concentration increases, acoustic waves are absorbed in sediment-laden flow and attenuated where the acoustic instrument cannot operate properly in high sediment concentrations. These limitations should be taken into consideration when predicting SSC using acoustic methods.

An ADCP estimates horizontal and vertical velocities as a function of depth by using the Doppler effect: a change in the observed sound frequency that results from relative motion toward or away from the sound source. An ADCP utilizes the Doppler effect by transmitting sound at a fixed frequency and listening to echoes returning from sound scatterers in the water so that the relative velocity between the instrument and scatterers in the water is measured. Velocity profiles are produced by dividing the echo into depth cells. Data are averaged vertically in each depth cell, the height of which is defined by the operator. For specifics of the instrument capabilities and configuration options, the reader is referred to the user's manuals (SonTek, 1998; RD Instruments, 2001).

The magnitude of acoustic reflection from the water (signal strength) is a function of the instrument used (influenced by frequency, transmit power, receive sensitivity, and range to the measurement volume) and the conditions of the water which is affected primarily by the type, size, and concentration of particulate matter.

Relative changes in suspended sediment can be determined directly from the changes in signal strength data, assuming a constant sediment type and size distribution. Signal strength data can be converted to measured suspended sediment concentration by comparing acoustic data to water samples and other instrumentation.

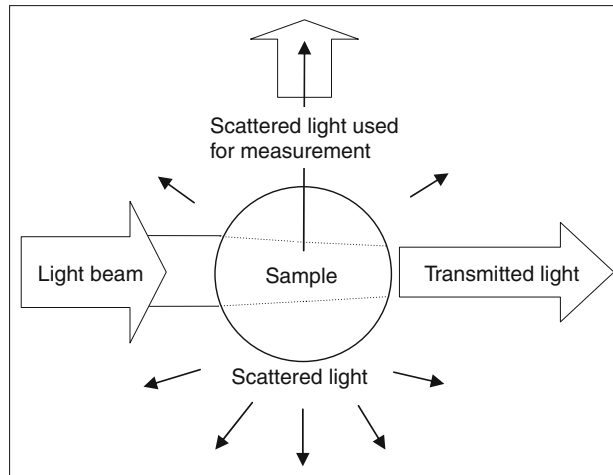
Recent research has been on the potential of ADCPs to estimate suspended sediment concentration and bed load (Alvarez and Jones, 2002; Creed et al., 2001; Kostaschuk et al., 2004; Rennie and Villard, 2004). However, these studies were limited to rivers and estuaries or the transport of sand and gravel. Measurements of bed load velocity using ADCPs have been compared with bed load samplers in sand and gravel reaches of a river (Kostaschuk et al., 2004). For gravel beds, bed load velocity was found to be correlated with sampler measurements, and the results were influenced by sediment size, although the effect of particle size was not investigated thoroughly. Studies conducted in estuaries (Alvarez and Jones, 2002; Creed et al., 2001) showed that ADCP performed better for the sediments which have the size distribution close to wavelength of the ADCP output frequency. Also, in both studies, signal strength of the ADCP was affected by salinity fluctuations, beside sediment particles in the water column. However, the effect of salinity was not investigated thoroughly. In a recent study conducted by the author (Elçi et al., 2009), different parameters affecting the performance of an ADV for the prediction of SSC are investigated through measurements made in different streams located in the Aegean region of Turkey having different soil types. A prediction model is presented in this paper relating signal to noise ratio (SNR) readings to SSC measurements where both water temperature and sediment characteristic type are incorporated into the model.

The primary barrier to the development of a comprehensive sediment concentration prediction method has been the lack of sufficient coupled observations of turbidity and acoustic Doppler velocity measurements to develop such a relation. Current methods (Kostaschuk et al., 2004; Rennie et al. 2002; Rennie and Villard, 2004) are capable of predicting SSC in rivers or canals, but application does not exist for stratified environments.

This paper discusses comparison of particulate matter quantity as received by the use of SonTek's RiverCat (1500 kHz ADCP system) and DKK-TOA's WQC-24 (multiparameter water quality meter). Its purpose is to improve the methodology used for prediction of sediment concentration by acoustic methods in stratified environments. Measurements of suspended sediment concentrations and flow velocities were conducted simultaneously when the boat was attached to a buoy in the lake. These measurements were repeated every month including the summer period, when the lake was strongly stratified.

Instrumentation

Measurements of SSC by a water quality meter and flow velocities by ADCP were made simultaneously at the lake. The water quality meter used here measures turbidity by using the scattered light measurement method (Figure 1). Turbidity measurements provide a reading of the amount of scattered light. Turbidity is expressed in terms of the optical property causing the light beam passing through the sample of the fluid to be scattered and absorbed



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 1 Illustration of scattered light measurement method and the instrument used for measurements.

rather than transmitted through the sample. In this study, turbidity measurements were made using DKK-TOA's multiparameter water quality meter. The data accuracy for turbidity was $\pm 3\%$. The relationship between the suspended solids in the liquid and the light intensity due to particle scatter is determined by the factory calibration of the instrument (1 NTU of turbidity corresponds to 1 mg/L of SSC). In the laboratory, the relationship between SSC and turbidity was tested, and a linear relationship was found (Elçi et al., 2009). Water quality data were recorded at 1-m intervals in the vertical. Time series measurements of water temperature and water quality data were recorded at 30-min intervals.

A SonTek ADCP (1.5 MHz) system was used in this study (Figure 2). A 1.5-MHz ADCP can operate to a profiling range (depth) of about 25 m which depends on the speed of sound, which is a function of water temperature, salinity, and sediment concentration. Data are averaged vertically in each depth cell defined by the user during the measurements. Averaging the data is important to reduce possible errors due to ADCP signal to noise ratio, frequency, depth cell size, number of pings averaged, and beam geometry.

Method

Signal strength data from current profilers were corrected for the depth at which suspended sediment concentrations were measured. Signal strength decreases with range from the system due to geometric spreading and absorption. The maximum profiling range for the system used was 15–25 m, varying according to the operating conditions of the ADCP. In Tahtali Lake, data were collected and stored internally and averaged every 5 sec with a cell size

of 0.5 m (Figure 3). The blanking distance of the instrument, where undefined data close to the transducer are blanked out, was 0.44 m.

Fifty cells were selected for this application since the lake was shallower than 25 m. The water depths at the sampling stations were determined by the bottom track option where the pulse hits the bottom. These depths were also verified by the depth sensor of water quality meter.

The water quality meter and the ADCP were synchronized, and the temperature, turbidity, and velocity readings were recorded. The suspended sediment concentrations were measured at the vertical profile within 1-min intervals (the shortest interval time that can be selected by the user). The SNR readings taken by the ADCP corresponding to these depths and times were selected, and the comparisons were made.

The profile of SSC was estimated using a multi-step process including:

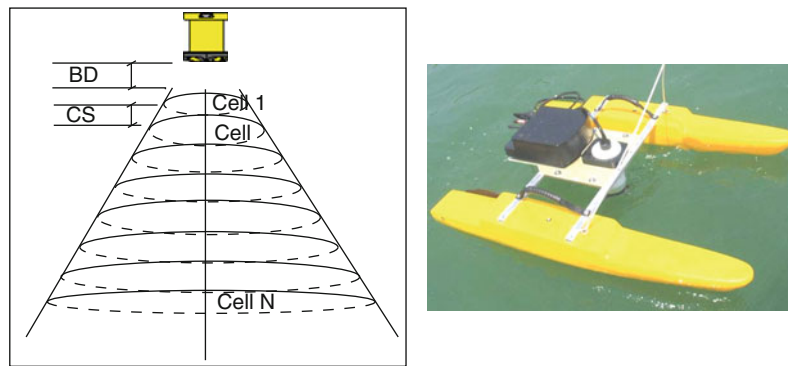
1. Calculating transmission loss from spreading and absorption as a function of range and absorption coefficient by the modified equation provided by SonTek (1997) (Equation 1) by a factor of C , where C is defined as a measure of stratification in the water column (Equation 2):

$$Decay = (-20 + C) \times \log 10 \left(\frac{D}{\cos \theta} \right) - 2\alpha \left(\frac{D}{\cos \theta} \right) \quad (1)$$

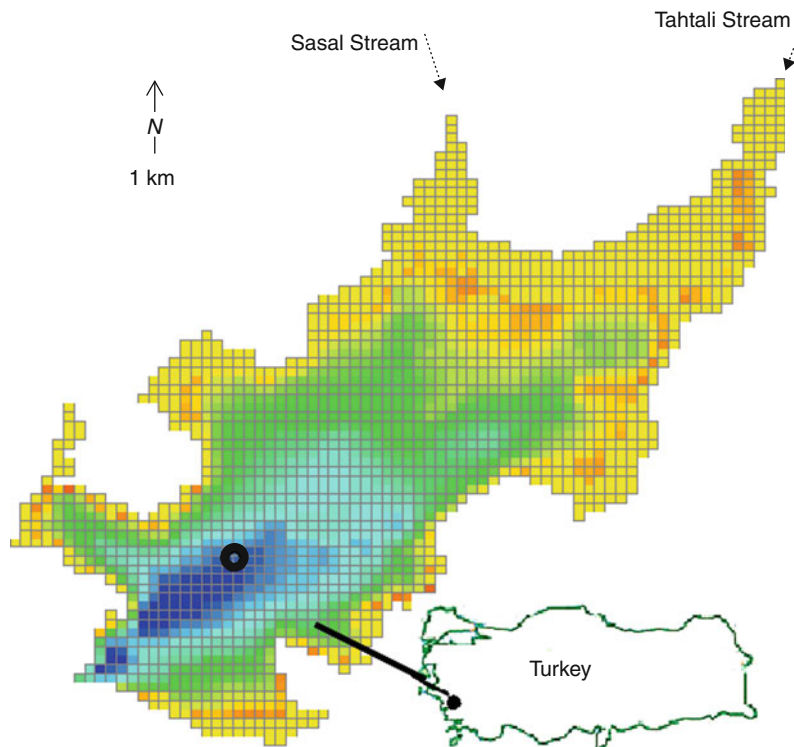
$$C = 20 \times \left(\frac{h_t}{h} - 0.5 \right) \quad (2)$$

where

$Decay$ = Predicted signal strength loss (dB)



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 2 Illustration of the operation of an ADCP and parameters used to determine ADCP down-looking profiling range and the system (RiverCat with fiberglass pontoons) used for measurements (From SonTek, 1997).



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 3 Bathymetric map of Tahtali Lake. The darker area represents the deepest region of the lake corresponding to 27 m. The buoy, where measurements were made, is shown by a circle.

D = Vertical range from the system (m)

θ = Transducer beam mounting angle (standard is 25°)

α = Absorption coefficient (0.6 dB/m for 1,500 kHz ADCP system)

$\frac{h_t}{h}$ = The ratio of depth of the epilimnion to the total depth of the water column

2. Determining relative backscatter from the velocity measurement for the water column and correcting for the transmission loss (decay)
3. Comparing to the turbidity data simultaneously measured with the ADCP and obtaining an equation for regression between measured turbidity and ADCP data

Close to the transducers, acoustic beams deviate from the spherical spreading in which acoustic signal is inversely proportional to distance from the transducers. This distance is given in Equation 3 by SonTek (1997):

$$d = \pi r^2 / \lambda \quad (3)$$

where r is the transducer radius ($r=2.4$ cm), and λ is the acoustic wavelength ($\lambda=1$ mm); d is calculated as 1.8 m. Therefore, it is necessary to consider the fact that ADCPs can not predict above this distance when estimating suspended sediment concentration at the near surface.

Study site

The observations were conducted in a thermally stratified water supply reservoir, Tahtali Reservoir in Turkey (Figure 3). Tahtali Dam was projected as a rockfill dam and completed in 1996 to supply fresh water to Izmir, the third largest metropolitan area with over three million population. The capacity of the dam is 175 million cubic meters, and it generates monthly five million cubic meters water. The dam is currently operated by IZSU (Izmir Water and Sewage Administration). Tahtali Reservoir has a surface area of 20 km², a mean depth of 15 m, with a maximum depth of 27 m. The major inflows are from North via Sasal Stream and Tahtali Stream. Sasal Stream contributes 25%, whereas Tahtali Stream contributes 75% to the total inflow. The discharges of the other four streams are negligible. The withdrawal point is at South-west location of the lake from the deepest area corresponding to 27 m. The water is provided as drinking water for the city of Izmir after being treated (Çaliskan and Elçi, 2009).

Field applications

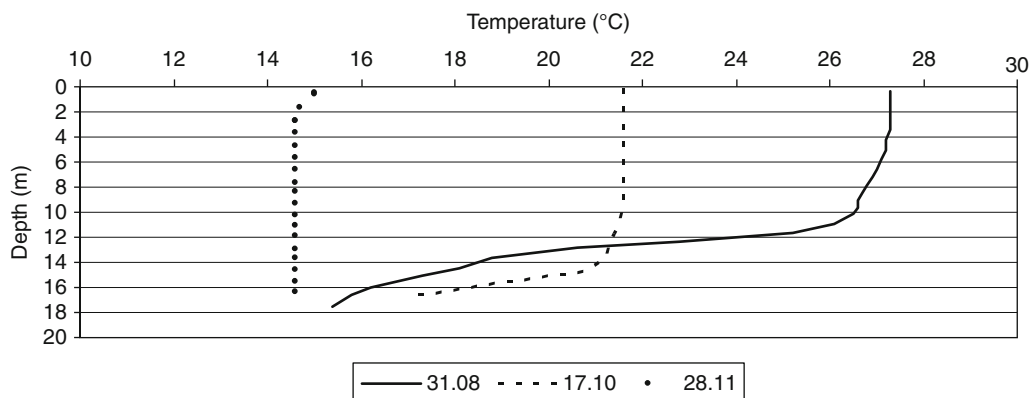
Examples of field applications are provided in Tahtali Lake where ADCP and the multiparameter water quality meter were deployed at monthly intervals to investigate the effects of stratification. The SNR readings and suspended sediment concentration data were measured

simultaneously when the boat was attached to a buoy in the lake. The location of the buoy is shown in the bathymetry map of Tahtali Lake (Figure 3).

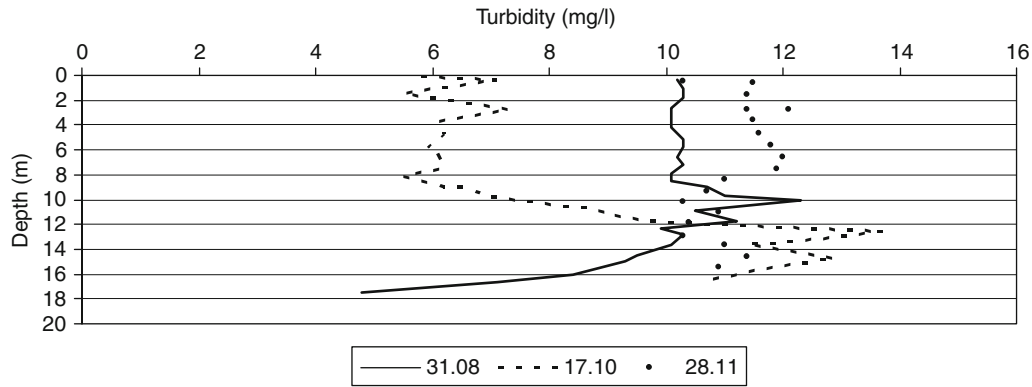
The observed temperature profiles at the buoy are given in Figure 4. Depth of the water column where buoy is located was 18 m. As one can see in the figure, stratification was evident in August where water temperature at the surface reached 28°C, and the thermocline started at a depth of 10 m. In October, however, surface temperatures decreased to 21.5°C, and the thermocline moved to a depth of 14 m, indicating mixing of most of the water column (Elçi, 2008).

The variation of turbidity profiles measured by the water quality meter is presented in Figure 5. Turbidity peaks are found mostly in the thermocline region. Turbidity increases are closely related to the maximum density gradient, which has the low turbulence level. A noticeable increase in turbidity toward the bottom of the lake on 17 October 2006 was probably due to the effect of the relatively cold sediment-laden water flowing into the lake after the rain event (no rain was observed in the study site from June to October 2006). Total of 3.5 mm rain was collected at the weather station during the last 3 days prior to the data collection on 17 October 2006, leading sediment concentration to double below the thermocline.

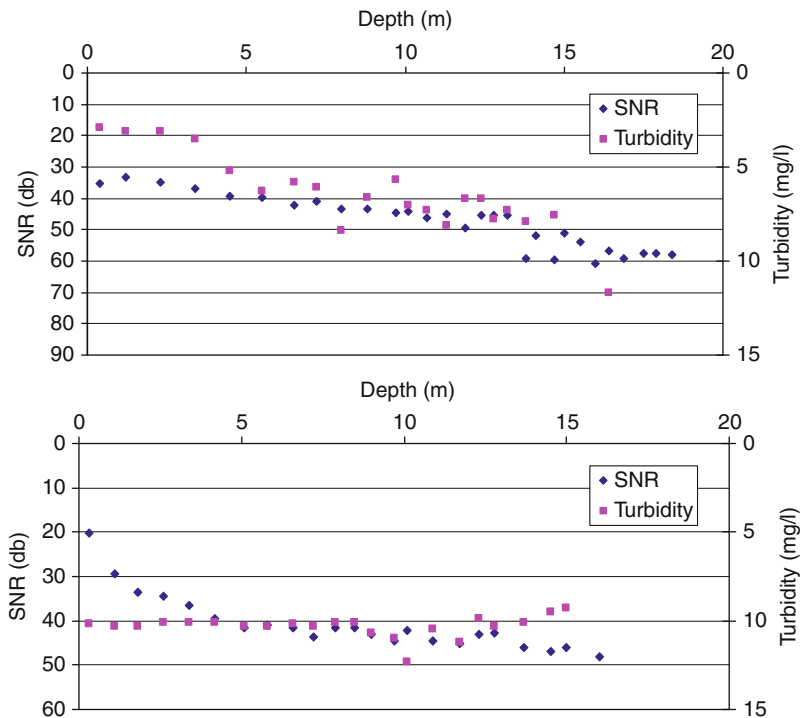
Figures 6 and 7 illustrate profiles of ADCP backscatter and suspended sediment concentration measured at a buoy on different dates. As can be seen in these figures, SNR data obtained from the RiverCat matched the turbidity data collected by the water quality meter well, especially within the thermocline. However, below the thermocline, turbidity values were underpredicted. This can be explained by the operation principle of the ADCP. The profiling range of the ADCP is a function of the acoustic frequency and the strength of the scattering return from the water. On 31 August 2006, for instance, thermocline had reached 10 m depth, and 12 mg/l was observed at that depth which was the maximum through the water column. From 10 m of depth to the bottom of the lake, the turbidity gradually decreased, indicating the decrease of the amount



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 4 The observed temperature profiles measured by the water quality meter at the buoy.



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 5 The variation of turbidity profiles measured by the water quality meter at the buoy.



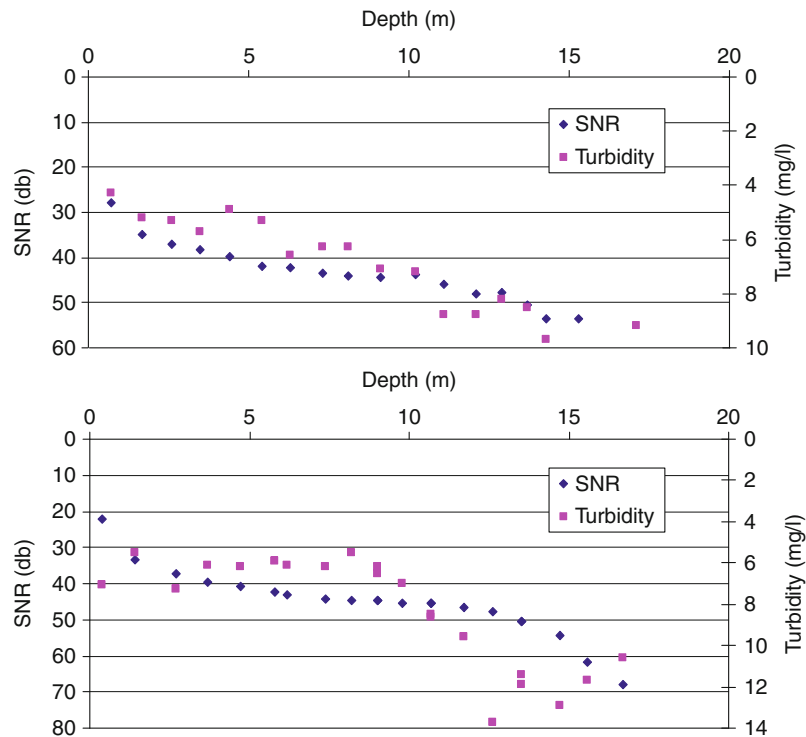
Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 6 Profiles of ADCP backscatter and suspended sediment concentration measured synchronously at a buoy on (a) 3 August 2006 and (b) 31 August 2006.

of the scatterers in the water column below 10 m. Variations in suspended sediment concentrations may change the absorption of the acoustic signal with range leading to underprediction of the turbidity close to the bottom.

The degree of relationship between two variables, SNR measurements provided by ADCP and turbidity

measurements provided by WQC, was investigated through correlation coefficient as follows (Equation 4):

$$correl(x,y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \quad (4)$$



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 7 Profiles of ADCP backscatter and suspended sediment concentration measured synchronously at a buoy on (a) 28 September 2006 and (b) 17 October 2006.

where x and y denote SNR and turbidity measurements respectively. The correlation coefficient was calculated for each data set and averaged to a single number. When only the water column above the thermocline was considered, the correlation coefficient was calculated as 0.85, and this number decreased to 0.65 when the whole water column was considered in the calculation. The best match was obtained on 28 September 2006 measurements. Considering only measurements on that date, the estimation equation is given below (Equation 5) ($R^2 = 0.83$):

$$SSC(estimated) = 0.3 \times SNR - 5, 2 \quad (5)$$

Effect of particle size

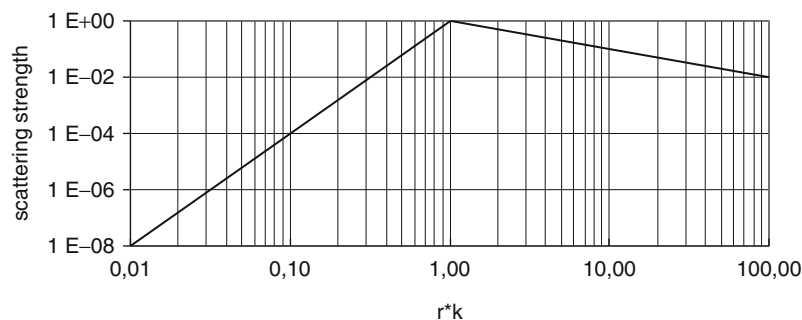
Acoustic frequencies have different sensitivities to particle size. Theoretically, the best results are obtained when $r * k = 1$, where r is the radius of the particle, and k is the acoustic wave number ($2\pi/\lambda$). For the current study, the corresponding acoustic wavelength λ is equal to 1 mm for the ADCP used and the best sensitivity expected for particle radius is close to 160 μm . Scattering strength of the equipment is provided by a simple model (SonTek, 1998) as shown in Figure 8. As can be seen in the figure, scattering strength decreases rapidly for particles smaller than 160 μm . Typical minimum particle size to be detected was 8 μm for the ADCP used in this study.

In order to determine the particle size distribution in the study site, soil samples were taken, and composite tests using both sieving and sedimentation methods were carried out. The air-dried sample of the soil is passed through different-size sieves, and the particles less than 0.075 mm were subjected to settle under gravity. Given by Stokes' Law, a falling particle reaches its terminal velocity that is proportional to the particle diameter. From the measurements at known time intervals, the distribution of particle size can be assessed. Based on this principle, hydrometer analysis was conducted in the lab for small particles. Particle size distribution of the samples collected at the banks of the Tahtali Lake is given in Figure 9. According to the results, soils of the study site can be described as sandy silt where more than 50% of the sample is finer than 0.075 mm; 28% of the soils are out of the detectable size of 8 μm .

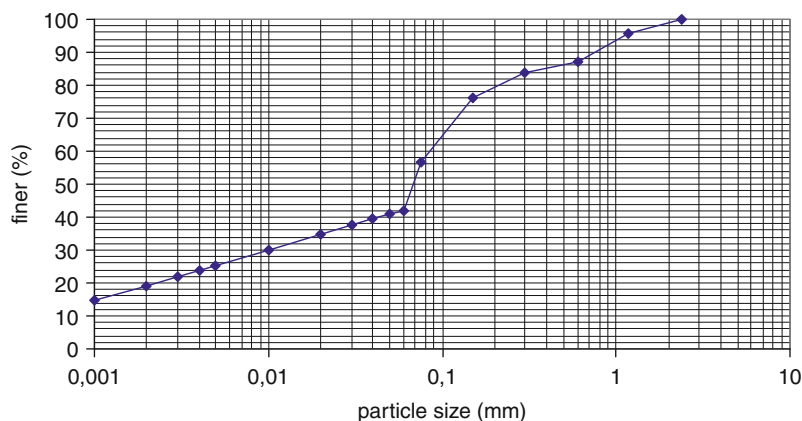
The changes in SNR data were attributed to changes in suspended sediment concentration rather than to changes in particle size distribution since the mean percentage of the material collected at the study site was less than 100 μm 90% of the time as obtained from the sieve analysis.

Discussions and conclusions

Comparison of particulate matter quantity as received by the use of ADCP system and measured with



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 8 Variation of scattering strength of the equipment with particle size (From SonTek, 1998).



Suspended Sediment Concentration in Stratified Lakes Estimated by Acoustic Methods, Figure 9 Results of the sieve analysis of the soil sampled in the study site.

multiparameter water quality meter was presented in the current study. Focus was given to stratified environments since previous studies lack observations in the stratified lakes. Results of this study showed that ADCPs can predict the suspended sediment concentration within the thermocline. However, below the thermocline, they failed to predict the formation. This can be explained by the effect of suspended sediment concentration variations on the absorption of the acoustic signal.

The limitation of this methodology, the incapability of ADCPs to differentiate between changes in concentration and changes in particle size distribution, was partly overcome by analyzing the soil samples taken from the study site and describing their particle size distributions. Samples taken from the study site indicated that the mean percentage of the material collected at the study site was less than 100 μm 90% of the time. Further research in different stratified lakes in different environments are required to assess whether the changes in SNR data are attributed to changes in suspended sediment concentration or to changes in particle size distribution.

This method would be beneficial especially in the sediment transport studies, since ADCPs are capable of

measuring time series of vertical water profiles, thus providing much more information for sediment structure as compared with the point measurements made with conventional turbidity meters.

Acknowledgments

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Cross-references

[Sedimentation Processes in Lakes](#)
[Turbidity Currents in Reservoirs](#)

SWEDEN'S GREAT LAKES

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Synonyms

Major lakes in Sweden

Definition

Sweden's great lakes. The four largest lakes in Sweden with regard to surface area are, in order, Vänern, Vättern, Mälaren, and Hjälmaren. Vänern is the third largest lake in Europe after Ladoga and Onega in Russia, and Vättern is the 11th largest lake. On a global ranking, Vänern is the 33rd and Vättern the 78th largest lake in the world (Herdendorf, 1982).

Introduction

Sweden has close to 100,000 lakes, where a lake is defined as a water body with a surface area greater than 0.01 km² (Lindkvist and Danielsson, 1987). Approximately 9% of the area of Sweden constitutes lakes, which corresponds to a total lake surface area of about 40,000 km². In total, 22 lakes have a surface area of more than 100 km², 358 lakes an area between 10 and 100 km², and 3,990 an area between 1 and 10 km². The ten largest lakes with regard to surface area, together with their volume and mean and maximum depths, are given in Table 1 (the exact numbers can vary somewhat since many lakes are regulated). The

Sweden's Great Lakes, Table 1 The ten largest lakes in Sweden according to surface area together with lake volume and mean and maximum water depths (* indicates lack of data; mainly after Lindkvist and Danielsson, (1987))

Lake name	Surface area (km ²)	Volume (km ³)	Mean depth (m)	Maximum depth (m)
Vänern	5,648	153	27	106
Vättern	1,912	77.6	41	120
Mälaren	1,140	14.3	13	66
Hjälmaren	484	3.0	6	20
Storsjön	464	8.0	17	74
Torneträsk	330	17.1	52	168
Siljan	290	8.1	28	134
Uddjaure	252	*	*	*
Hornavan	250	11.9	46	221
Akkajaure	242	*	*	92

deepest lake in Sweden is Hornavan with a maximum depth of 221 m and a surface area of 250 km². This lake, which is located in the very north of Sweden where all the deepest lakes are found, is the third largest with regard to volume, but only the ninth largest if the surface area is considered.

Besides being important parts of the ecosystem, the lakes in Sweden are often utilized in a variety of human activities (Willen, 2001). Lakes are used for water supply both in municipal and industrial applications, as well as in irrigation occasionally. Their recreational value is substantial, supporting the local economy through the tourism they generate and sustain. Historically, early settlements developed at the major lakes because they provided opportunities for fishing and transportation, which in turn promoted trade and economic growth. As the urban areas rapidly developed in the nineteenth and early twentieth century, the lakes functioned as receiving waters for a wide range of pollution discharge, mostly untreated wastewater. In the 1950s, the pollution levels in many lakes were becoming a problem and treatment plants were introduced to remove pollutants in the wastewater before release to the lakes (Persson et al., 1989). The continuous expansion of treatment plants with increasing sophistication, where more and more of the pollutants are being removed, has to a large degree restored the initial water quality of the lakes.

Many lakes in Sweden have been formed in depressions associated with fault lines or uneven deposition of material in connection with the melting of the ice cap that covered Scandinavia during the latest glaciation. Thus, tectonic movement together with effects related to glaciation has determined morphometric properties of the lakes that to a large degree control different lake processes such as *circulation*, *stratification*, through-flow, and lake *mixing* and residence time. During the melting of the ice cap (deglaciation), large amount of water was released, simultaneously, as sediment transported with the water was deposited downstream the ice margin. Subsequently, after the ice cap melted, the land mass that was depressed

by the ice experienced a rebound (an uplift) creating a vertical shift of the land relative to the sea level. This rebound is still going on in Sweden today and it has been of great significance for the development of the lakes (Bengtsson, 1984).

The water *circulation* in the lakes, and the associated *mixing*, is affected by different *hydrodynamic* processes, including water inflow, convective currents from temperature differences, wind, and *seiching* (Rubin and Atkinson, 2001). Water inflow tends to have only local effects with little implications for the basin-scale motion. In contrast, convective currents resulting from seasonal changes in the heat transfer between the lake surface and the atmosphere initiate motion on the scale of the lake. Most Swedish lakes that are not shallow are subject to thermal *stratification* in the summer followed by complete *mixing* in the fall as the temperature drops in the atmosphere. Also, in the winter, lakes may become ice-covered, especially in Northern Sweden, again leading to *stratification* with the occurrence of complete *mixing* during the ice breakup in the spring (Bengtsson and Svensson, 1996).

The wind induces large-scale *circulation* as it blows over the water surface, creating shear stresses that initiate water motion in the downwind direction. Simultaneously, surface waves are generated that may grow to substantial heights, if the lake area is large. In Sweden, large waves are typically found in Vänern and Vättern, where fetch lengths (i.e., the distance the wind blows over to build up waves) are the greatest. Besides inducing a drift at the water surface, the wind causes a tilt in the mean water level with increasing deviation from the still water level in the downwind direction. In a stratified lake, this displacement of the water surface causes an associated tilt in the thermocline, several orders of magnitude greater. *Seiching* may be induced, at the water surface or the thermocline, if the lake water surface is inclined and the wind stops blowing.

The four largest lakes in Sweden are Vänern, Vättern, Mälaren, and Hjälmaren (see Figure 1). Together they have a surface area corresponding to almost 25% of the total lake surface area in Sweden. The four lakes are more or less distributed around a straight line from Stockholm on the east coast of Sweden to Gothenburg on the west coast. During the deglaciation, a connection existed along this line between the Baltic Sea and the North Sea during several periods (Björck, 1995). The Baltic Sea discharged its water to the North Sea through this connection, which appeared about 9,000–11,000 years ago, and it had a great influence on the properties of these lakes.

In the following, the main characteristics of the four largest lakes are briefly presented with focus on the morphometry and hydrology, as well as the major processes governing the *circulation* and *stratification* in the lakes. Table 2 summarizes key hydrological data for the four lakes according to Kvarnäs (2001).

Lake Vänern

Vänern is the largest lake in Sweden with a surface area of 5,648 km², a mean depth of 27 m, and a total volume of 153 km³. The inflow to Vänern originates from the largest catchment in Sweden encompassing almost 47,000 km², that is, more than 10% of the area of Sweden, although some part of the catchment is located in Norway. The outflow occurs through the Göta River providing the largest mean flow rate (about 500 m³/s) for any river in Sweden. Based on the lake volume and the through-flow, the lake residence time has been calculated to be approximately 10 years (Kvarnäs, 2001). Vänern consists of two subbasins that are separated by a shallow area containing a multitude of islands, which markedly influences the dynamics of the water *circulation* in the lake. The lake was regulated in the middle of the 1930s for hydropower purposes.



Sweden's Great Lakes, Figure 1 Map over the location of the four largest lakes in Sweden.

Sweden's Great Lakes, Table 2 Key hydrological data for Sweden's great lakes (mainly after Kvarnäs, 2001)

	Vänern	Vättern	Mälaren	Hjälmaren
Drainage area (km ²)	46,830	6,359	22,603	4,053
Surface runoff (l/s/km ²)	11.6	6.6	7.4	6.6
Outlet flow (m ³ /s)	516	42	168	27
Residence time (years)	9.8	58	2.8	3.7
Water level amplitude (m)	1.7	0.28	0.95	0.6
Precipitation (mm)	631	510	533	502
Evaporation (mm)	541	442	470	502

Direct precipitation on the lake corresponds to about 25% of the inflow from the catchment, and the river Klarälven contributes with 35% of the inflow. The Vänern catchment is located in a region where snow is common during the winter, leading to a marked peak in the runoff during the spring when the accumulated snow is melting. However, all the major rivers discharging into the lake are regulated, implying that the flow peak is attenuated in time.

Vänern is large enough to be influenced by the rotation of the earth. Thus, wind-induced currents may be affected by the Coriolis force, leading to a geostrophic *circulation* in the counterclockwise direction (Lindell and Welch, 1992). If the lake is stratified, this *circulation* also causes the thermocline to deform from its horizontal level. Geostrophic *circulation* has not been observed in any of the other large Swedish lakes, probably because of size, geometry, and shoreline configuration.

Thermal *stratification* occurs annually in Vänern, primarily in the summer. In August, the depth to the thermocline in the lake is about 15 m (mean depth 27 m). During some years, Vänern becomes completely ice-covered, but typically it is only in the coastal areas where ice develops. In the spring, a special type of horizontal *stratification* in the shallow areas known as a *thermal bar* may occur (Malm et al., 1998). Water in the shallow parts of the lake is heated up more quickly than the deeper parts and a vertical barrier (bar) between 4-deg water in the deeper parts and warmer water in the shallow parts emerges. This barrier moves offshore as the heating continues in the shallow parts. The *thermal bar* is typically present during a month (Kvarnäs, 2001). When the lake becomes completely ice-covered, slow-moving currents may still develop, although the effects of wind are absent (Bengtsson, 1996).

Lake Vättern

Vättern is the second largest lake in Sweden with a surface area of 1,912 km², a mean depth of 41 m, and a total volume of 78 km³. The catchment supplying water to Vättern is 6,359 km², implying that the ratio between the catchment area and the lake surface area is 3.3, which is

considerably smaller than for the other large lakes. Thus, the annual volume of direct precipitation on the lake surface is almost equal to the inflow. Vättern has an elongated shape with only one basin and relatively few islands, and the lake is oriented in the SSW-NNE direction with a maximum length of about 130 km. The lake was regulated in the late 1930s.

The annual mean flow through the lake is small with respect to the lake volume, resulting in a residence time that is rather long (58 years) compared to other Swedish lakes. Thus, seasonal or annual variations in the inflow to Vättern have limited effects on the water quality, since it takes considerable time before the inflow can contribute a runoff volume comparable to the lake volume. The main inflow is through the Huskvarna River and an adjacent smaller lake system, whereas the outflow occurs via Motala River to the Baltic Sea.

Seiching has been observed in Vättern and the period of the lowest mode is estimated to be about 180 min with maximum amplitude of 13 cm (Norrman, 1964). Subsequent studies have shown the presence of higher-order modes with periods of 98 and 81 min (Björk and Lundberg, 1990). Internal *seiching* in the thermocline also occurs where vertical movement of 15 m is possible at the ends of the lake (Kvarnäs, 2001). Strong winds may generate short-period surface waves of significant heights because of the relatively long fetch in the longitudinal direction of the lake. Theoretically, the significant wave height has been estimated to be over 2.0 m for wind speeds at 21 m/s (Norrman, 1964). The waves are often steep, that is, the wave height is large with respect to the wavelength, which could cause problems for boats.

Similar to Vänern, Vättern is seldom ice-covered during the winter, except in the coastal areas, and vertical *stratification* with a distinct thermocline primarily develops during the summer. In August, the depth to the thermocline is about 16 m (mean depth 40 m). The epilimnion (upper layer) temperature in Vättern is the lowest among the four largest lakes (just below 12°), since deeper lakes have larger heat storage capacity, implying a slower heating up (and cooling down).

Lake Mälaren

Mälaren is the third largest lake in Sweden with a surface area of 1,140 km², a mean depth of 13 m, and a total volume of 14 km³. The Mälaren catchment is almost 20 times larger than the lake surface area, which is the largest ratio among the great lakes of Sweden (e.g., the corresponding ratio for Vänern is 8.3). Mälaren has a complicated shoreline configuration since it was created through a number of faults generating fissures in the north-south direction. Thus, it is possible to identify five subbasins that have emerged as a result of tectonic movement and glacial processes (Kvarnäs, 2001), and the lake contains a large number of islands. Mälaren was first regulated in the beginning of the 1940s, and an important aim of the regulations has been to avoid saltwater intrusion from the Baltic Sea at low lake levels.

Having the largest catchment with respect to the lake surface area, direct precipitation on the lake surface has only a minor effect on Mälaren. The precipitation is about 10% of the inflow from the catchment. Mälaren is almost ice-covered every year and because of the thermal *stratification* that develops during the winter, oxygen deficit occurs in some parts of the lake. The *stratification* in the summer results in a thermocline that is located at 12 m water depth in August. Mälaren was the first Swedish major lake where water quality sampling was carried out in a systematic and comprehensive manner. This sampling was performed in the mid-1960s. After some years, water quality studies were also initiated in Hjälmaren and Vättern, followed by Vänern in the early 1970s (Willen, 2001).

Lake Hjälmaren

Hjälmaren is the fourth largest lake in Sweden with a surface area of 484 km², a mean depth of 6 m, and a total volume of 3 km³. The ratio between the catchment area and the lake surface area is 8.4, which is similar to Vänern. The lake has five subbasins with a number of fault zones extending in the east–west direction, with the northern part of the lake having a multitude of islands (Kvarnäs, 2001). The water that exits Hjälmaren enters into Mälaren trough Eskilstuna River, providing about 35% of the input flow to Mälaren. Hjälmaren was regulated at the end of the nineteenth century with the purpose of generating more agricultural areas. This led to a general decrease in the mean water level of about 1.3 m.

Hjälmaren is also ice-covered during most winters, whereas the limited water depth typically prevents development of a thermal *stratification*, even during the summer.

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Cross-references

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SWEDISH GLACIAL LAKES: ESTIMATION OF THE NUMBER OF LAKES OF DIFFERENT SIZES

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Introduction and Aim

How many lakes are there in Sweden? Such seemingly nonsensical questions are discussed in the scientific literature. But what is the relevance of the question? It may very well be nonsensical from many perspectives but not if one would like to use such estimates to determine the breeding grounds for toads, mosquitoes, beavers, or wild orchids. The basic aim of this section is to provide an estimate of the total number of lakes in Sweden. The method to do this concerns transformations, regressions, and extrapolations (Håkanson and Peters, 1995).

Major lake types on earth

Practically all lakes in Sweden have been influenced by the enormous form-creating power of the latest glaciation. All these lakes will, in due course, be filled up and vanish. Hutchinson (1957) has discussed all major lake types, their origin, morphometric characteristics, and distribution on Earth. He differentiated between 11 major lake types that were divided into 76 subtypes. The 11 major lake types are summarized in Table 1. Most lakes on Earth appear in glacial landscapes.

Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes, Table 1 Major lake types on Earth according to Hutchinson (1957)

1. Tectonic lakes, e.g., basins in faults (like Lake Bajkal and Lake Tanganyika).
2. Volcanic lakes, e.g., maars, caldera lakes and lakes formed by damming of lava flows.
3. Landslide lakes, e.g., lakes held by rockslides, mudflows, and screes.
4. Glacial lakes:
 - A. lakes in direct contact with ice, e.g., lakes on or in ice and lakes dammed by ice.
 - B. Glacial rock basins, e.g., cirque lakes and fjord lakes.
 - C. Morainic and outwash lakes, e.g., lakes created by terminal, recessional, or lateral moraines
 - D. Drift basins, e.g., kettle lakes and thermokarst lakes.
5. Solution lakes, e.g., lakes formed in caves by solution.
6. Fluvial lakes:
 - A. Plunge-pool lakes.
 - B. Fluvial dams, e.g., strath lakes, lateral lakes, delta lakes and meres.
 - C. Meander lakes, e.g., oxbow lakes and crescentic levee lakes.
7. Aeolian lakes, e.g., basins dammed by wind-blown sand and deflation basins.
8. Shoreline lakes, e.g., tombolo lakes and spit lakes.
9. Organic lakes, e.g., phytogenic dams and coral lakes.
10. Anthropogenic lakes, e.g., dams and excavations made by man.
11. Meteorite lakes, e.g., meteorite craters.

Number of lakes in Sweden

The geographical distribution of all the Swedish lakes is shown in Figure 1. It is evident that the country of Sweden in many ways has its character from these many lakes. This is true also in many other countries dominated by glacial lakes, e.g., Finland, northern Russia, Canada, and northern U.S.A.

Table 2 divides the lakes in Sweden into different classes according to lake area (there are 3 lakes larger than 1,000 km²: Vänern, Vättern, and Mälaren; 19 lakes between 100 and 1,000 km², etc.). The data given in Table 2 have been used to illustrate the relationship between lake area and number of lakes (Figure 2a): There is a clear, logical quantitative relation between lake size and the number of existing lakes in the given size categories.

By making different types of transformations of the x- and y-parameters in this plot, it is possible to obtain a very good linear regression. This is shown in Figure 2b, which gives area^{0.05} on the x-axis and cumulative number (Cum. number^{0.1}) on the y-axis. The r²-value (the coefficient of determination) is 0.999. The regression line is: $y = -3.834 \cdot x + 6.147$. Many different types of transformations and exponents have been tested for the x- and y-parameters. From this, one can estimate the number of lakes in Sweden larger than 0.1 ha in area. This extrapolation (Figure 2b) suggests that 227,000 such lakes exist in



Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes, Figure 1 Lakes in Sweden larger than 1 km². The map was kindly provided by SMHI (Swedish Meteorological and Hydrological Institute).

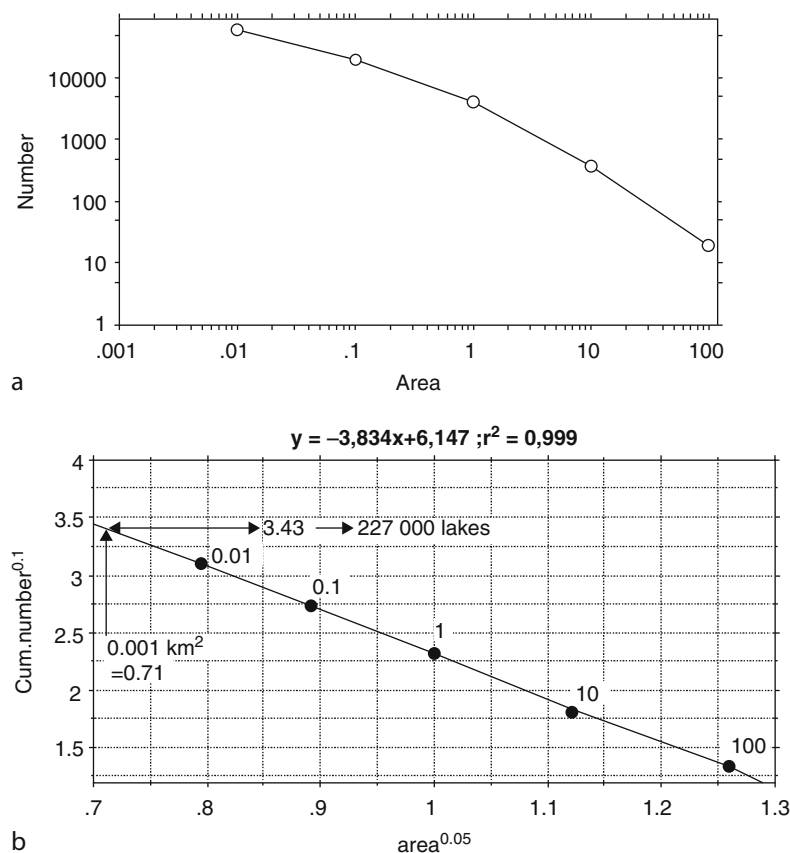
Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes, Table 2 The number of lakes in Sweden arranged by size (Håkanson and Peters, 1995)

Area (1 km ² = 100 ha)	Number	Cumulative number
>1,000	3	3
100–1,000	19	22
10–100	362	384
1–10	3,987	4,371
0.1–1	19,374	23,745
0.01–0.1	59,500	83,245
0.001–0.01	144,000	227,000

Sweden. One can also estimate that there exist about 520,000 lakes and ponds larger than 100 m².

It is also easy to estimate the total area of these lakes from the number of lakes within a given size class and the mean (or median) area of the size class.

Despite its high r², this relationship, like all empirical relationship, is only valid for lakes of this type, i.e., glacial



Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes, Figure 2 (a) Relationship between lake area and number of lakes in Sweden in the given size classes. (b) A regression between lake area ($\text{area}^{0.05}$) and cumulative number of lakes in Sweden in the given size classes ($\text{Cum. number}^{0.1}$). The r^2 -value is 0.999. The number of lakes in Sweden larger than 0.1 ha is estimated to be 227,000 from this plot.

Swedish Glacial Lakes: Estimation of the Number of Lakes of Different Sizes, Table 3 Morphometrical data for the four largest Swedish lakes (From Håkanson, 1979)

	Vänern	Vättern	Mälaren	Hjälmaren
Total area (km ²)	5,893	1,898	1,617	492.9
Open water area (km ²)	5,648	1,856	1,096	477.8
Volume (km ³)	153	74.0	14.0	2.89
Maximum depth (m)	106	128	63	22.0
Mean depth (m)	27.0	39.8	12.8	6.05
Large islands (>1 km ²), number	20	6	43	4
Total area (km ²)	177.8	36.2	9.03	9.03
Islands (1–0.01 km ²); number	793	81	354	95
Total area (km ²)	54.7	4.65	4.51	4.51
Small islands (1–0.01 ha); number	8,772	813	1,248	963
Total area (km ²)	11.8	0.96	1.21	1.21
Rocks (<0.01 ha); number	12,100	10,999	6,584	14,546
Total area (km ²)	0.58	0.52	0.31	0.36

lakes (see Table 1). One could guess that similar results would be obtained for other parts of the world influenced by glacial activity. Such lakes are by far the most common lake type on Earth.

Islands in glacial lakes

Table 3 gives key morphometrical data for the four largest Swedish lakes: Vänern (which is the fourth largest lake in Europe), Vättern, Mälaren, and Hjälmaren and the table

also gives the number of islands in these glacial lakes. One can note that there are more than 20,000 islands (and rocks) in Lake Vänern. Also note the clear relationship between size and number of islands in the lakes: There are relatively few large islands with a relatively large total area and there are many small islands and rocks with a relatively small total area. This relationship between size and number is typical for lakes from glacial landscapes.

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Cross-references

[Finnish Lakes](#)

[Sweden's Great Lakes](#)

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TANGANYIKA LAKE, MODELING THE ECO-HYDRODYNAMICS

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Introduction

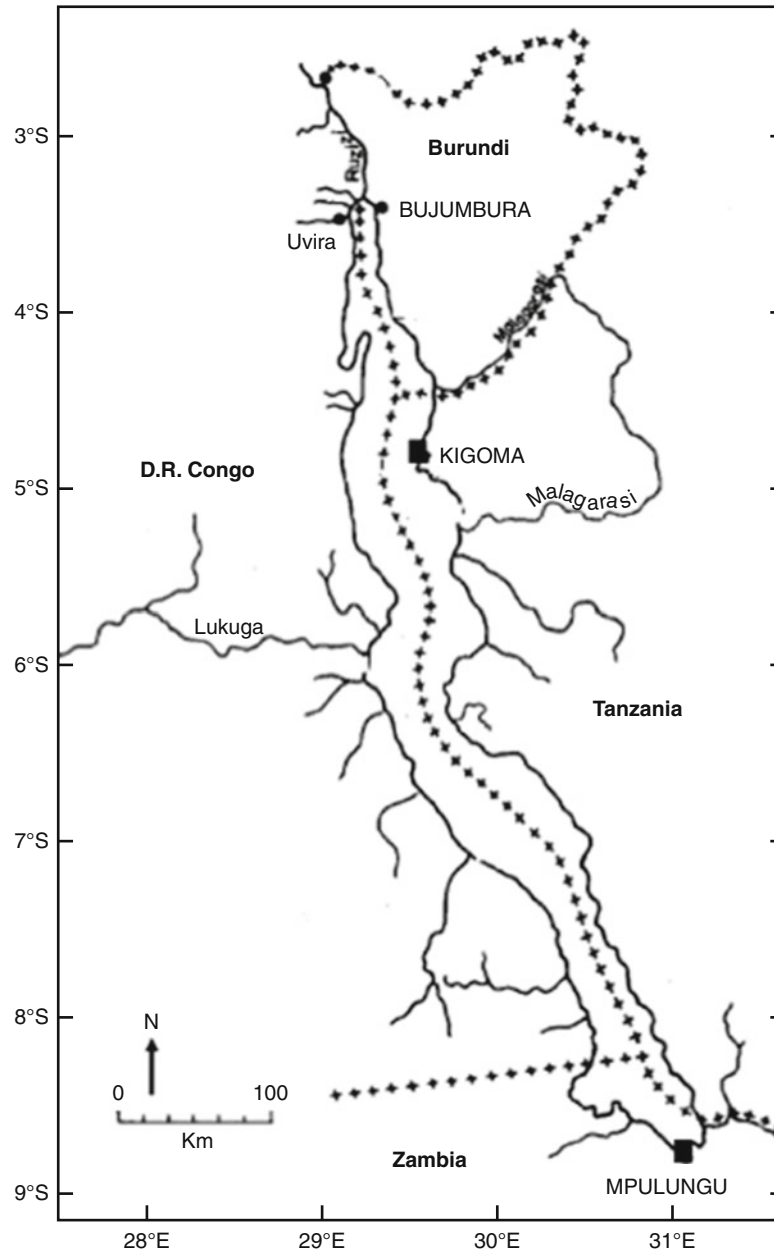
Lake Tanganyika is one of the Great Rift Valley Lakes of East Africa (Figure 1) and is situated between 3°S and 9°S. It is 650 km long with a mean width of around 50 km and an average depth of 570 m. It is a freshwater Lake characterized by a quasi-permanent thermocline. The Lake is meromictic – complete overturning of the water never takes place – and mixing occurs only partially. The epilimnion (surface layer) undergoes seasonal temperature change annually, while the hypolimnion is anoxic with an invariant temperature. The hypolimnion is a vast reservoir of nutrients largely isolated from surface influences (Hecky and Fee, 1981; Hecky et al., 1991). The average transparency of the Lake is close to 11 m. The solar radiation around the Lake varies very little in the year because of its closer proximity to the equator. The nutrients supplied to the mixed layer, where photosynthesis can occur, are mainly internal nutrients from within the Lake, whereas riverine and atmospheric input of nutrients is considered negligible for Lake Tanganyika (Hecky and Fee, 1981; Sarvala et al., 1999a; Langenberg et al., 2003a). Nutrients from the hypolimnion are supplied to the epilimnion mainly by wind-driven upwelling of the strong southeast winds during the dry season from March/April

until August/September (Hecky et al., 1991; Plisnier et al., 1999; Langenberg et al., 2003b). The wind stress pushes the warmer surface water away from the southern end of the Lake toward the northern end, resulting in a well-known compensating upwelling in the south. This upwelling results in the seasonal enhancement of the nutrients in the euphotic layer initiating phytoplankton blooms. Apart from this major wind-induced southern upwelling, small coastal upwellings can also be seen from time to time propagating clockwise around the western boundaries of the lake, which are the internal Kelvin wave packets (Naithani and Deleersnijder, 2004). During the wet season, the primary production is less important and is primarily dependent on the nutrients regenerated within the epilimnion (Coulter and Spigel, 1991).

The above mentioned thermodynamic, hydrodynamic, and ecological characteristics are incorporated into an eco-hydrodynamic model to study the primary food web of Lake Tanganyika. The hydrodynamic model comprises nonlinear, reduced-gravity equations (Naithani et al., 2002, 2003). The ecological model components include one nutrient, phytoplankton biomass, zooplankton biomass, and detritus (Naithani et al., 2007a, b, 2011).

Materials and method

The model consists of a four-component ecosystem model, coupled to a hydrodynamic model. The hydrodynamic model considers the Lake as two homogeneous layers of different density lying above each other, representing the warm epilimnion (surface mixed layer) and cold dense hypolimnion (lower layer) separated by a thermocline (Naithani et al., 2002, 2003). The lower layer is considered to be much deeper than the surface active/mixed layer. The model is forced with the wind and solar radiation data from the NCEP reanalysis. Studies using the hydrodynamic model have shown that in the motion of water there are internal waves with oscillations similar to that in the forcing



Tanganyika Lake, Modeling the Eco-hydrodynamics, Figure 1 Geographic map of Lake Tanganyika.

winds (Naithani et al., 2002, 2003). The simulated oscillations compare satisfactorily with those derived from observed temperature in the Lake (Naithani et al., 2002, 2003). The coupled ecological-hydrodynamic model simulations show also good correspondence with the measurements from the Lake (Naithani et al., 2007a, b).

The hydrodynamic model equations are:

$$\frac{\partial \xi}{\partial t} + \frac{\partial(Hu)}{\partial x} + \frac{\partial(Hv)}{\partial y} = w_e \quad (1)$$

$$w_e = \left(\frac{3}{20}\right)^{1/2} \frac{(\tau_x^2 + \tau_y^2)^{1/2}}{(\varepsilon g H)^{1/2}} - w_d - \frac{\xi}{r_{tt}} \quad (2)$$

$$\begin{aligned} \frac{\partial(Hu)}{\partial t} = & -\frac{\partial(Huu)}{\partial x} - \frac{\partial(Hvu)}{\partial y} + fHv - gH \frac{\partial \xi}{\partial x} \\ & + \frac{\partial}{\partial x} \left(HA_x \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(HA_y \frac{\partial u}{\partial y} \right) + \frac{\tau_x}{\rho_0} + w_e^- u \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial(Hv)}{\partial t} = & -\frac{\partial(Huv)}{\partial x} - \frac{\partial(Hvv)}{\partial y} - fHu - gH \frac{\partial \varepsilon \xi}{\partial y} \\ & + \frac{\partial}{\partial x} \left(HA_x \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(HA_y \frac{\partial v}{\partial y} \right) + \frac{\tau_y}{\rho_0} + w_e^- v \end{aligned} \quad (4)$$

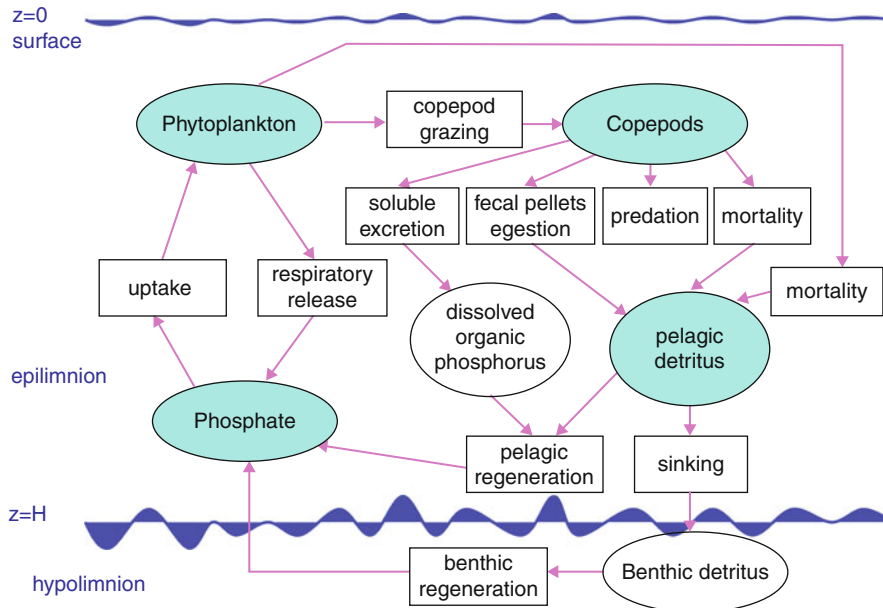
where x and y are horizontal axes, u and v are the depth-integrated velocity components in the surface layer in the x and y directions, t is the time, x is the downward displacement of the thermocline, $H = h + \xi$ is the thickness of the epilimnion (the surface, well-mixed layer), h is the reference depth of the surface layer (m), and w_e is the entrainment velocity (ms^{-1}). The first term on the right hand side of Equation 2 is inspired by Price (1979), τ_x and τ_y are horizontal components of specific wind stress in the x and y direction (m^2s^{-2}), and $\varepsilon = (\rho_b - \rho_s)/\rho_b$ is the relative density difference between the hypolimnion (ρ_b) and the epilimnion (ρ_s), calculated using the temperature of the surface layer (t_s) and bottom layer (t_b) respectively. w_d is the detrainment term (ms^{-1}), defined such that the annual mean of the epilimnion volume remains approximately constant. There are large uncertainties in the parameterization of entrainment and detrainment terms. As a consequence, to avoid occasional spurious values of ξ , a relaxation term (ξ/r_{tt}) is needed which slowly nudges the surface layer depth toward its equilibrium position. The relaxation timescale, r_{tt} , is sufficiently long so that the relaxation term is generally smaller than the entrainment and detrainment terms. f is the Coriolis factor (<0 in the southern hemisphere), and A_s is the horizontal eddy viscosity in the s ($=x,y$) direction.

The ecosystem model (Figure 2) consists of dissolved phosphorus (*Phos*), phytoplankton (*Phyto*), zooplankton (*Zoo*), and detritus (*Detr*) (Naithani et al., 2007b). Phosphorus was the only nutrient simulated in the model to trigger phytoplankton growth (Järvinen et al., 1999). The phytoplankton processes include primary production (*PROD*), respiration (*RESP*), and mortality (*MORT_a*). The processes concerning the zooplankton are grazing (*GRAZ*), fecal pellet (*FEC*) egestion, excretion (*EXC*), and mortality (*MORT_z*). Phytoplankton respiratory release and the excretion from zooplankton are directly remineralized in the surface layer. A small percentage of feces, dead phytoplankton, and zooplankton are also remineralized into phosphate in the surface layer whereas the rest contributes to the detritus pool, which sediments fast. The regeneration/remineralization within the surface layer represents the effect of the microbial food web and also represents the pelagic regeneration. The model is closed by predation (*PRED*) from zooplanktivorous fish and sinking of detritus out of the surface layer. The zooplanktivorous fish biomass is assumed equal to that of zooplankton biomass (Sarvala et al. 1999a).

The ecosystem model equations are:

$$\begin{aligned} \frac{\partial(H\text{Phyto})}{\partial t} = & -\frac{\partial(Hu\text{Phyto})}{\partial x} - \frac{\partial(Hv\text{Phyto})}{\partial y} \\ & + \frac{\partial}{\partial x} \left(HK_x \frac{\partial \text{Phyto}}{\partial x} \right) + \frac{\partial}{\partial y} \left(HK_y \frac{\partial \text{Phyto}}{\partial y} \right) + \phi_{he} \\ & + H\{\text{PROD} - \text{RESP} - \text{MORT} - \text{GRAZ}\} \end{aligned} \quad (6)$$

$$\text{PROD} = r_p \min[2F(I), F(P)]\text{Phyto} \quad (7)$$



Tanganyika Lake, Modeling the Eco-hydrodynamics, Figure 2 Flow diagram of the ecological parameters considered in the model.

$$RESP = r_a r_p \min[2F(I), F(P)]Phyto \quad (8)$$

$$MORT_a = m_a Phyto \quad (9)$$

$$GRAZ = r_z \frac{Phyto}{Phyto + k_{phyto}} Zoo \quad (10)$$

$$F(P) = \frac{Phos}{Phos + k_{phos}} \quad (11)$$

$$F(I) = (1/k_e H) [\arctan(\alpha I_0 / 2I_k) - \arctan(\alpha I_0 e^{-k_e H / 2.1_k})] \quad (12)$$

$$k_e = 0.066 + 0.07 \frac{Phyto}{r_c} \quad (13)$$

$$\phi_{he} = w_e^+ Phyto_h + w_e^- Phyto \quad (14)$$

$$\begin{aligned} \frac{\partial(HZoo)}{\partial t} = & -\frac{\partial(HuZoo)}{\partial x} - \frac{\partial(HvZoo)}{\partial y} \\ & + \frac{\partial}{\partial x} \left(HK_x \frac{\partial Zoo}{\partial x} \right) + \frac{\partial}{\partial y} \left(HK_y \frac{\partial Zoo}{\partial y} \right) + \phi_{he} \\ & + H \{ GRAZ - EXC - FEC - MORT_z - PRED \} \end{aligned} \quad (15)$$

$$EXC = n_e GRAZ \quad (16)$$

$$FEC = n_f GRAZ \quad (17)$$

$$MORT_z = m_z GRAZ \quad (18)$$

$$PRED = r_f \frac{Zoo}{Zoo + k_{zoo}} Fish \quad (19)$$

$$\begin{aligned} \frac{\partial(HPhos)}{\partial t} = & -\frac{\partial(HuPhos)}{\partial x} - \frac{\partial(HvPhos)}{\partial y} \\ & + \frac{\partial}{\partial x} \left(HK_x \frac{\partial Phos}{\partial x} \right) + \frac{\partial}{\partial y} \left(HK_y \frac{\partial Phos}{\partial y} \right) \\ & + \phi_{he} + H \left\{ \frac{-(PROD - RESP)}{CP_a} + \left(\frac{p_a MORT_a}{CP_a} \right. \right. \\ & \left. \left. + \frac{(p_f FEC + p_z MORT_z + EXC)}{CP_z} \right) \right\} \end{aligned} \quad (20)$$

$$\begin{aligned} \frac{\partial(HDetr)}{\partial t} = & -\frac{\partial(HuDetr)}{\partial x} - \frac{\partial(HvDetr)}{\partial y} \\ & + \frac{\partial}{\partial x} \left(HK_x \frac{\partial Detr}{\partial x} \right) + \frac{\partial}{\partial y} \left(HK_y \frac{\partial Detr}{\partial y} \right) + \phi_{he} \\ & + H \{ (1 - m_p) MORT_a + (1 - p_f) FEC \\ & + (1 - p_z) MORT_z - r_d Detr \} - w_d Detr \end{aligned} \quad (21)$$

The first four terms on the right hand side of Equations 6, 15, 20, and 21 represent the horizontal advection and diffusion of the ecological parameters, u and v are time-dependent horizontal velocities obtained from the circulation model, and K_x and K_y are the horizontal

diffusion coefficients. The fifth term represents entrainment from hypolimnion. Entrainment of phosphate from the hypolimnion was extrapolated exponentially from $45 \mu\text{gPL}^{-1}$ below 60 m depth to $1 \mu\text{gPL}^{-1}$ near the surface (Coulter and Spigel, 1991; Plisnier et al., 1996; Plisnier and Descy, 2005). This ensured that the water is richer in nutrients if upwelling occurs from deeper depths. The definition of the parameters and their values are given in Table 1. Model was run with the thermocline at 30 m and the temperature of the surface and lower layers as 27°C and 24.5°C , respectively for the years 2002–2009.

Results and discussion

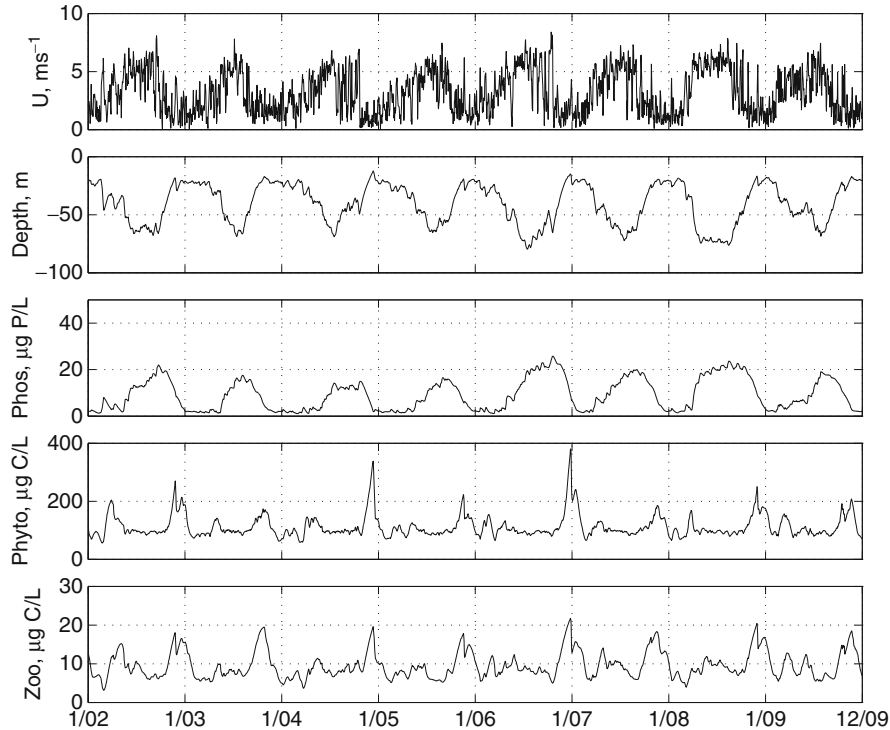
Figure 3 shows the time series of wind speed, model predicted surface layer (epilimnion) depth, and the depth-averaged concentration in the surface layer of phosphate, phytoplankton biomass, and zooplankton biomass. The surface layer depth increases at the beginning of the dry season because of wind driven mixing and remains at greater depth during the whole season. It decreases at the end of the dry season and remains more or less at this depth during the wet season until the beginning of the next dry season. Phosphate concentration closely follows the mixed layer depth. It increases because of entrainment associated to the upwelling of nutrients from below and remains high for the rest of the dry season, because of almost continuous upwelling, and decreases at the end of the dry season. Increase in the biomass of phytoplankton at the beginning of the dry season is natural because of the input of nutrients in the surface layer. However, the phytoplankton biomass cannot sustain at this high value and decreases in spite of the continuous abundance of nutrients. The increased surface layer depth caused by persistently higher winds forced the algal community to spend more time in deeper water with reduced light, thereby decreasing the productivity. Phytoplankton biomass shows another bloom at the end of the dry season when the SE wind diminishes and, subsequently, changes direction, and the surface layer still carrying adequate amounts of nutrients relaxes back to shallower depths (Plisnier et al., 1999). Phytoplankton biomass in effect showed a trade-off between the availability of nutrients and light. Negative effects of deep mixing on the phytoplankton biomass were also considered by Sarvala et al. (1999b).

Effect of changing the model ecological parameters

Increasing (decreasing) the half-saturation constant for grazing decreased (increased) the zooplankton biomass and increased (decreased) phytoplankton biomass (Naithani et al., 2007a). The change in the phytoplankton biomass is almost half the change in the zooplankton biomass. Decreasing the predator population increases the zooplankton biomass and vice versa. For these tests with the predator population the change in the phytoplankton biomass is much less than the change in the zooplankton biomass. It is seen that the primary production, which

Tanganyika Lake, Modeling the Eco-hydrodynamics, Table 1 Governing parameters, their description, value, and units used in the model

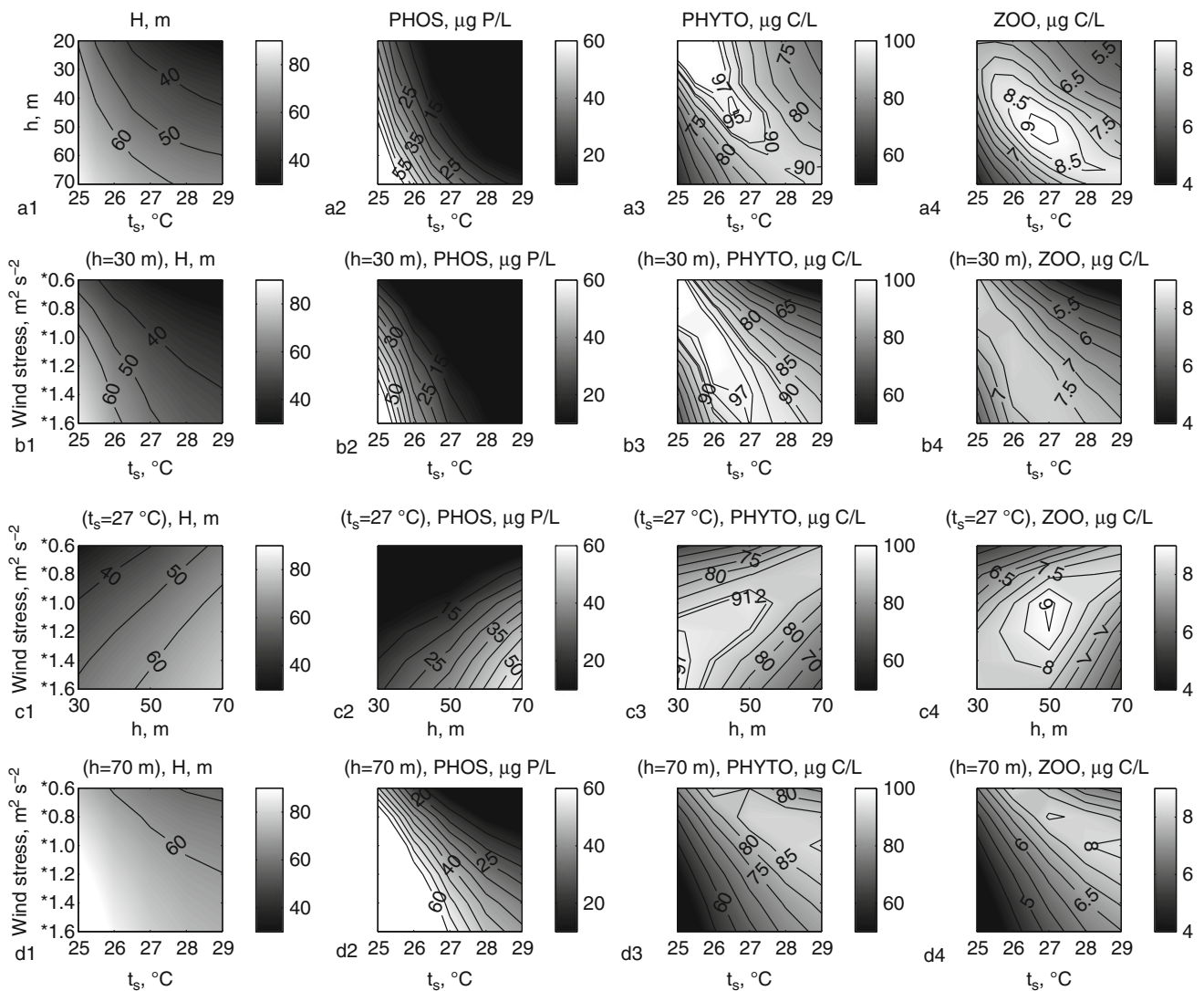
Symbol	Parameter	Value	Unit
α	Coefficient accounting for the photosynthetic activity	0.56	—
CP_a	C/P ratio of phytoplankton	58.1	—
CP_z	C/P ratio of zooplankton	77.42	—
I_o	Incident light radiation at the air-water interface	Variable	$\mu\text{E m}^{-2}\text{s}^{-1}$
I_k	Light saturation constant	375	$\mu\text{E m}^{-2}\text{s}^{-1}$
k_e	Light extinction coefficient	Variable	m^{-1}
k_{phos}	Half-saturation constant, uptake	5.0	$\mu\text{g P L}^{-1}$
k_{phyto}	Half-saturation constant, grazing	50.0	$\mu\text{g C L}^{-1}$
k_{zoo}	Half-saturation constant, predation	5.0	$\mu\text{g C L}^{-1}$
m_a	Percentage of phytoplankton mortality	0.15	—
m_z	Percentage of zooplankton mortality	0.1	—
n_e	Percentage of ingestion regenerated as soluble excretion of zooplankton	0.3	—
n_f	Percentage of ingestion egested as faecal pellets	0.3	—
p_a	Percentage of remineralized dead phytoplankton in water column	0.8	—
p_f	Percentage of remineralized faecal pellets in water column	0.4	—
p_z	Percentage of remineralized dead zooplankton in water column	0.8	—
$Phyto_{min}$	Phytoplankton threshold for grazing	15.0	$\mu\text{g C L}^{-1}$
r_a	Percentage of respiration	0.15	—
r_c	Carbon/Chla ratio	100.0	—
r_d	Benthic remineralization rate	0.02	day^{-1}
r_f	Maximum predation rate	0.2	day^{-1}
r_p	Maximum uptake/growth rate of phytoplankton	1.4	day^{-1}
r_z	Copepod grazing rate	0.57	day^{-1}
w_d	Detritus sinking rate	-12.0	m sec^{-1}
Zoo_{min}	Zooplankton threshold for grazing	2.0	$\mu\text{g C L}^{-1}$

**Tanganyika Lake, Modeling the Eco-hydrodynamics, Figure 3** Time variation of the Lake averaged parameters over a period of 8 years, from 2002 until 2009.

strongly depends upon the light in the water column and entrainment of nutrients, is bottom-up controlled, while it seems that predator abundance strongly controls zooplankton biomass (top-down control, Naithani et al., 2007a). By contrast, fish predation influence seems reduced on the phytoplankton level. In other words, any change in predator biomass significantly affects the herbivore biomass, but has little influence on phytoplankton biomass. Indeed, in our simulations, reduced grazing pressure from top-down control of mesozooplankton did not increase phytoplankton abundance considerably. In planktivore-dominated Lake Tanganyika, zooplankton are not able to control phytoplankton, and therefore, light or nutrient limitation and resource competition seem to be common among the latter (Järvinen et al., 1999).

Effect of changing the physical parameters

Various tests of the model using different physical parameters (thermocline depth, surface layer temperature, and wind velocity) are summarized in Figure 4. Any change in these physical forcing parameters modifies the timing and intensity of the dry season blooms of the biogeochemical parameters (Naithani et al., 2011). Increasing t_s or the wind stress delays the phytoplankton peak. Increasing the reference thermocline depth (h) increases the entrainment of phosphate from below and decreases the phytoplankton biomass. Increasing/decreasing the surface layer temperature decreases/increases the depth of the upper mixed layer and the entrainment of phosphate (Naithani et al., 2011). This decreases the phytoplankton biomass. The phytoplankton growth is favored at low t_s for a shallower



Tanganyika Lake, Modeling the Eco-hydrodynamics, Figure 4 Lake averaged parameters for various h and t_s (a1–a4), for wind stress varying by the factor indicated in the ordinate and t_s , at $h = 30$ m (b1–b4), for various wind stress and h (c1–c4), and for various wind stress and t_s , at $h = 70$ m (d1–d4).

thermocline and high t_s at a deeper thermocline. Increasing wind stress favors phytoplankton production because of deeper mixing.

An increase in temperature will decrease the phytoplankton and zooplankton biomass. This is because high temperature will result in shallower thermoclines, thereby decreasing the mixing probabilities with the nutrient-rich bottom water (Livingstone, 2003; Verburg et al., 2003; Verburg and Hecky, 2009). Lower temperature will lead to deeper lying thermocline thereby forcing the algal community to spend more time in the low light conditions at greater depths. Decreasing wind stress also has a negative effect on the growth. However, if these high temperatures are accompanied by stronger winds, the resulting wind mixing will bring the nutrients up to the euphotic zone allowing a greater primary production.

Conclusions

The behavior of the model-simulated parameters reflects that the dominant components responsible for the phytoplankton biomass in the lake are temperature stratification, availability of light and nutrients. Primary production in the nutrient-depleted surface layer depends upon the recycling of nutrients by wind-induced vertical mixing. The transport and mixing events are critical for the resupply of nutrients for the primary productivity and biogeochemical processes in the stratified lake. Increasing stratification decreases mixing and entrainment of nutrients from the hypolimnion. At too high light conditions at shallower depths, linked to higher surface layer temperature, the phytoplankton growth was limited by nutrients. Inversely, at higher nutrient levels at deeper depth, associated with low surface layer temperature, phytoplankton production was limited by light. The most favoring surface layer depth for the biomass production was found to be between 40 and 60 m (Figure 4). This depth seems to be linked to optimal light and nutrient conditions allowing phytoplankton production and an increase in its biomass. High winds are important for the supply of nutrients to the euphotic zone in the Lake. They are also linked with increased internal wave activities and turbulence. This could induce an increased temporal patchiness in the primary production (short moments when primary production could be very high). So the average seasonal condition should not be considered when investigating phytoplankton growth. But short-term strong wind events could also be important for local blooms in phytoplankton.

It can be inferred that a slight increase in temperature will still be bearable for Lake Tanganyika ecosystem, as long as the wind is strong enough to mix water and bring nutrients from the hypolimnion to the epilimnion. Otherwise, the primary production will decrease.

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TANGANYIKA LAKE: STRONG IN HYDRODYNAMICS, DIVERSE IN ECOLOGY

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Introduction

Lake Tanganyika (Figure 1) is one of the few ancient lakes in the world (estimated age 9–12 million years; Cohen et al., 1993). It is the second in size of the African Great Lakes and also second in depth among lakes in the world. It locates at an altitude of 773 m above m.sl. The drainage area is 263 000 km². The lake is 650 km long and 50 km wide in average. It has three main basins. In the north, the Kigoma basin extends to the depth of 1,310 m. The middle basin is separated from the Kigoma basin by a broad sill with a depth of 655 m, and in the south, from the Kipili basin by another sill with a depth of 700 m. The basin near Kipili is the deepest of the three basins, its maximum depth being 1,470 m. The lake is meromictic with stable hypolimnetic waters, and the salt content is low for this type of lake (Coulter, 1991).

The early studies from the beginning of the last century have been summarized by Coulter (1991). Later, a Belgian exploration in 1946–1947 proved the existence of internal waves in the thermocline as they measured the lake water temperature. Another result of the same expedition was the first bathymetric chart of the lake by Figure 1. In the late 1950s, Dubois collected the first depth-time series of temperature and oxygen data. In the early 1960s, Coulter (1963) continued the studies in the south, and later on, in 1973–1975, in the northern part of the lake.

Lake Tanganyika was studied intensively during 1990s as part of the Lake Tanganyika Research for the Management of Fisheries (LTR) by FAO and also as part of Lake

Tanganyika Biodiversity Project/LTBP by UNDP/GEF (www.fao.org/fi/ltr (LTR) and <http://www.ltbp.org/> (LTBP)). Water level fluctuations and meteorological data were collected at Bujumbura (Burundi), Kigoma (Tanzania), and Mpulungu (Zambia). Limited meteorological observations were conducted also in Uvira (DR Congo), Kalemie (DR Congo), and Kipili (Tanzania). Data on the thermal regime of the lake waters were collected with two moored buoy stations and also with a CTD-profiler near field stations, as well as from the research vessel during the expeditions. Data on water currents were collected with flow cylinders, which were used intensively near the field stations and also on lake-wide expeditions. During LTBP, also acoustic Doppler current profilers (ADCP) were used both on board and at moored stations.

Later four Finnish universities have arranged several field courses in Kigoma, Tanzania.

The CLIMLAKE “Climate Variability as Recorded by Lake Tanganyika,” funded by the Belgian Science Policy, included a 3-year survey of the lake over the period 2002–2004. Also hydrodynamic and ecological models were developed for the lake. The aim of the project was to understand the Lake Tanganyika variability and sensitivity to climate change. Another Belgian project, CLIMFISH was active in years 2004–2006.

Meteorological conditions

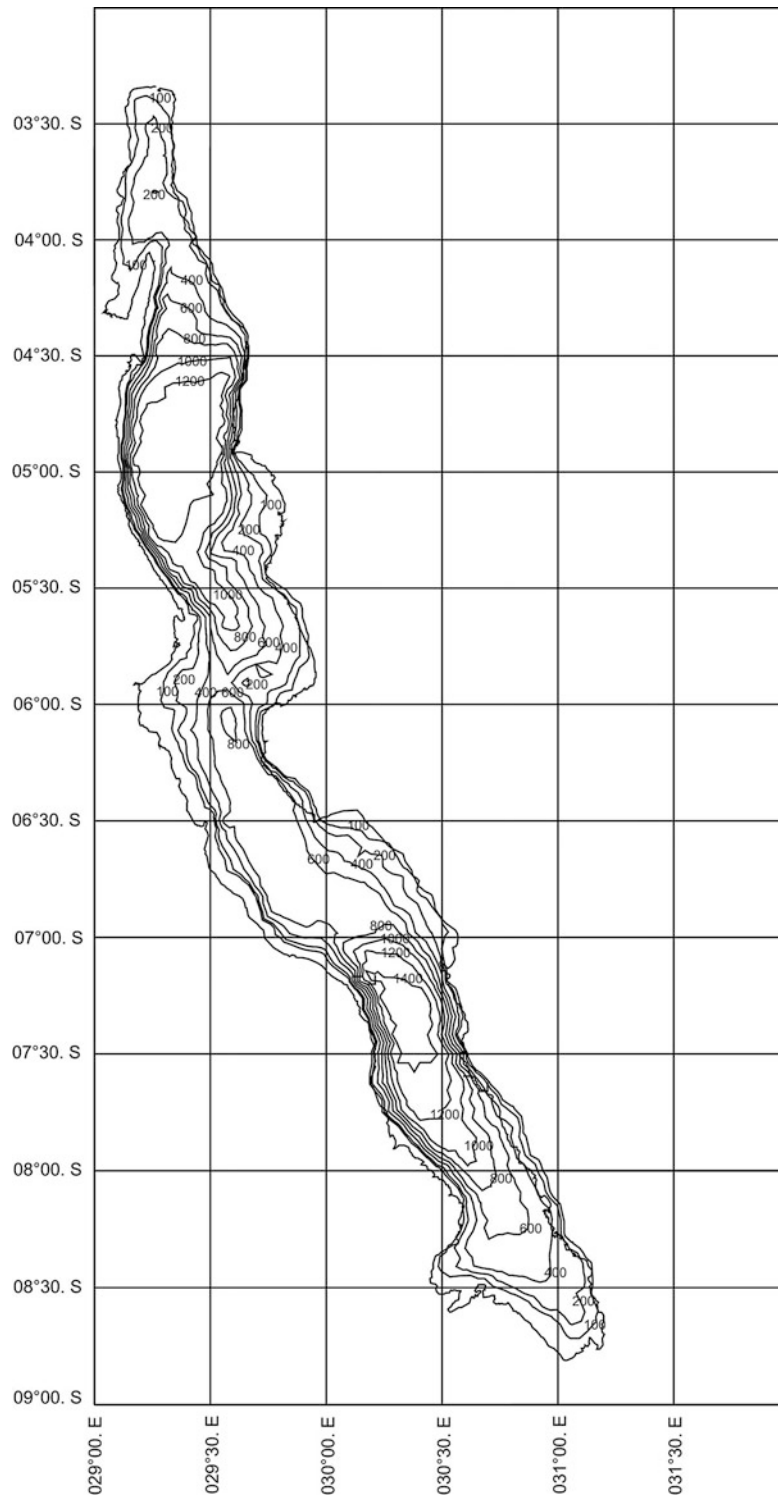
There are two main seasons with different weather conditions within the yearly cycle in the Lake Tanganyika region. The wet season from October to April is characterized by weak winds over the lake, high humidity, considerable precipitation, and frequent thunderstorms (Figure 2). The dry season from May until the end of August is characterized by little precipitation and strong, regular southerly winds. The seasonal changes of weather and winds result from large-scale atmospheric processes, especially of the position of the global tropical wind convergence zone.

The diurnal cycle of winds is also well developed in Tanganyika region. The studies of Savijärvi (1995 and 1997) and Podsetchine et al. (1999) revealed that the mountain slopes contributed about 50% and the trade winds 25% to the diurnal variation of winds. The rest 25% of the wind variation was due to the lake effect. The SE trade wind enhances the lake breeze considerably at daytime and adds on the downslope winds at nighttime.

Thermal regime

The seasonal thermal regime of the lake has been discussed by Capart (1952), Coulter (1963, 1991), Huttula (1997), Plisnier et al. (1999), Langenberg et al. (2002), Verburg et al. (2003), and Verburg and Hecky (2009).

Heating of the lake takes place mainly in the beginning of the wet season in October–November (Coulter, 1991; Huttula, 1997). Thermal stratification prevails all over the lake. The thermocline is situated at the depth of

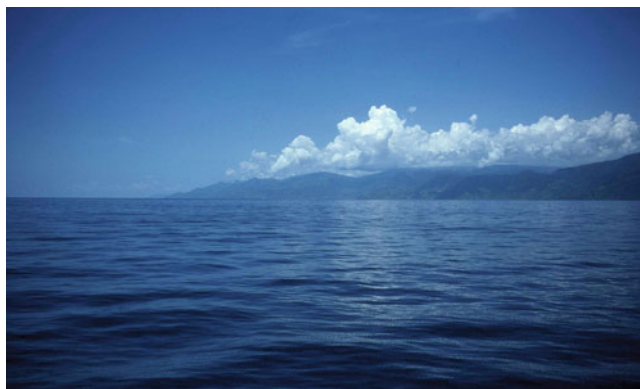


Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology, Figure 1 Bathymetric map of Lake Tanganyika.

40–60 m. The lake loses heat through evaporation caused by strong winds during the dry season (Coulter, 1991). This cooling is strongest in the southern basin. In the epilimnion, the temperature varies between 25°C in August

and 27°C in April. In the hypolimnion, the temperature varies only between 23.43 and 23.48°C.

During lake-wide expeditions in the 1990s, the water temperature data revealed a clear down-tilting of the



Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology, Figure 2 Lake Tanganyika scenery on a calm sunny day in the wet season (Photo Jouko Sarvala).

thermocline (on an average 4 cm/km) in dry season from S to N along the main axis of the lake (Huttula, 1997). This corresponded with the findings of Coulter (1963, 1968) from more than 30 years earlier. Higher temperatures and deeper depth of certain isolines indicated increased heating of waters over the years. Also O'Reilly et al. (2003) have discussed the heating of the lake and decreasing wind speeds and consequent significant increase of lake water stability during the last century. The transverse eastward down-tilting was observed in the Kalemie strait both in the wet season and the dry season as high current speeds were observed. This tilting was obviously connected to the uninodal internal seiche in the lake.

Hydrodynamics

Upwelling in Lake Tanganyika has been observed at the very southern end of the lake during the dry season in May–August.

The stability of 70% of the lake volume and the great age of the lake should lead to a high depth gradient of salts. However, several studies show that no such gradient exists in the lake's deep waters, which indicates some kind of deep water circulation. Tietze (1982) estimated that the decrease in density due to temperature changes within the metalimnion was about 1 kg m^{-3} and that density variations due to dissolved substances were 5% of those due to temperature variations.

The most extensive hydrodynamic measurements were conducted during the LTR (Huttula, 1997). A uninodal surface seiche was observed with a period of 4.7 h with a phase shift of 180° between Bujumbura in the north and Mpulungu in the south. The observed uninodal internal seiche period at Mpulungu buoy was 23.4 days during dry season (Fig. 3). During wet season, the period was much longer, 34.8 days. At Kigoma buoy data allowed to determine the period only for wet season, when it was 26.3 days (Podsetchine and Huttula, 1996).

The vertical mixing conditions and stratification varied seasonally and from year to year, with strongest mixing

during the dry season. Interannual variation was seen in the years 1993–1996 off Mpulungu, where mixing intensity decreased for each successive year (Verburg et al., 1998).

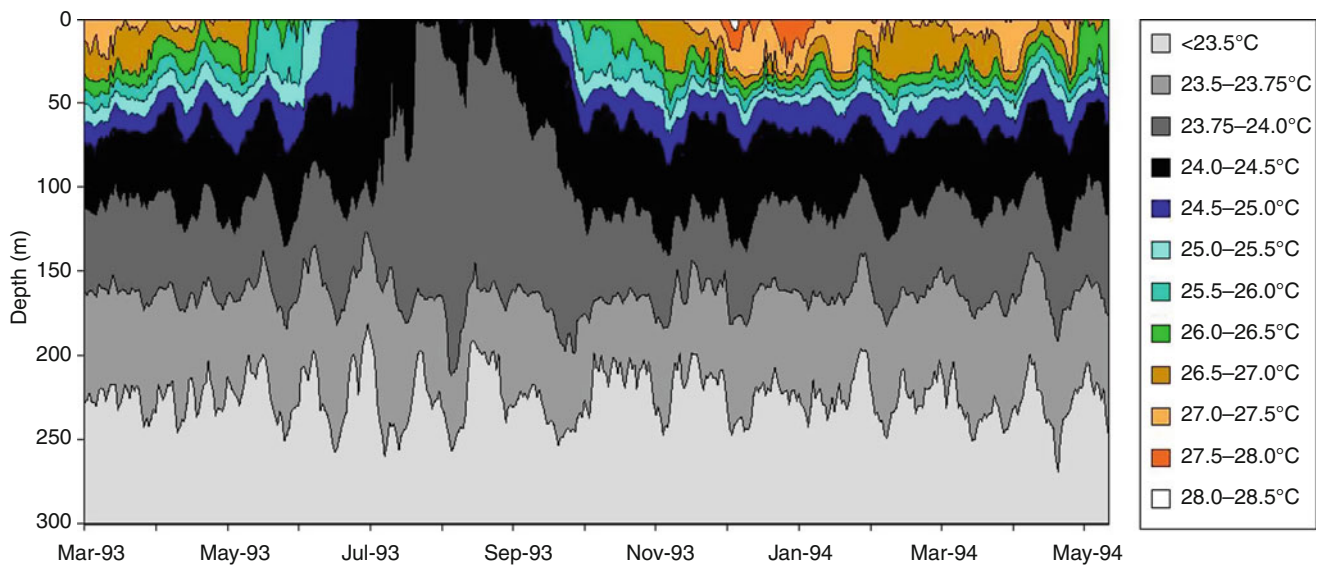
High Resolution Limited Area atmospheric Model (HIRLAM) was used for driving the 3D lake flow and transport model and regional flow and sediment transport models near the Malagarasi river mouth, as well as in the Mpulungu bay (Huttula, 1997). Model validation was carried out for the wet season (April 1997) and dry season (August 1997). Several mesoscale gyres were observed in the lake. Diurnal variation of surface water currents was observed at several sites such as the shallow waters near Malagarasi, Rusizi, and even the deeper inlet area of Lufubu. The local lake-land breeze system highly dominated the short-scale current field in the lake. The seasonal variation of the current field was observed to act as superimposed on this local system. In the dry season, the discharge of the river waters and suspended particulate matter (SPM) concentration in river waters were low. The simulations showed that, at this time, the dilution and the advection of river waters happen in the vicinity of the river mouths. Gravitational settling, advective transport by wind-induced currents, and turbulent diffusion are the main governing factors generating the zones of higher suspended solids concentration mainly in shallow areas near river and creek outlets. The great depth of the lake reduces the probability of erosion and resuspension of settled solid particles to limited shallow areas near shoreline.

Naithani et al. (2007) proposed an eco-hydrodynamic (ECOH) model for Lake Tanganyika to study the plankton productivity. The hydrodynamic sub-model solves the nonlinear, reduced-gravity equations in which wind is the dominant forcing. The ecological sub-model for the epilimnion comprises nutrients, primary production, phytoplankton biomass, and zooplankton biomass. In the absence of significant terrestrial input of nutrients, the nutrient loss is compensated for by seasonal, wind-driven, turbulent entrainment of nutrient-rich hypolimnion water into the epilimnion, which gives rise to high plankton productivity twice in the year, during the transition between two seasons.

The pelagic ecological system is highly dynamic

Lake Tanganyika is home to more than 2,000 plant and animal species, a large number of them endemic. The fish community comprises 250 cichlid and 75 non-cichlid species, 98% and 60% of which, respectively, are endemic. Most of the diversity resides in the narrow littoral zone around the perimeter of the lake, while the pelagic food web, on which the fish production is mainly based, is extremely simple for a lake of this size (Coulter, 1991).

The pelagic ecosystem of Tanganyika is very patchy and dynamic, both physically and biologically. Limnological conditions and planktonic resources exhibit high spatial and temporal variability at various time scales (Descy et al., 2005; Bergamino et al., 2007).



Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology, Figure 3 Water temperature isolines (°C) based on daily means. Period from March 1993 to May 1994 from Mpulungu buoy. (From Huttula, 1997.)

Phytoplankton production is to a large extent based on nutrients supplied from the anoxic hypolimnion through various mixing processes (Coulter, 1991). Accordingly, on short time scales, the dominant control on productivity is wind-driven, dry season upwelling, while in the long-term productivity is controlled by external loading determined by changes in precipitation (Langenberg et al., 2003; Cohen et al., 2006). Wind-driven gradual change in physical and chemical properties of the productive zone along the north–south axis creates regional variation in nutrient flows and plankton community structure and affects food web functioning (Coulter, 1991; Langenberg et al., 2008). Strong coupling of meteorological data and water column properties was also confirmed by Nahimana et al. (2008).

Planktonic copepods may show eight or more abundance peaks during a year (Mölsä et al., 2002). Both zooplankton and fish perform extensive diel vertical migrations (Coulter, 1991; Vuorinen et al., 1999), and variable horizontal aggregations are characteristic of the fish populations, particularly the schooling clupeid *Stolothrissa* (Plisnier et al., 2009). However, at longer time periods, at the scale of fish generation times (from about one to several years), the system appears rather stable (Sarvala et al., 2002). Lake Tanganyika, together with Lake Baikal, is the least disturbed and most pristine ecosystem of the Great Lakes of the world, although even Tanganyika is subject to anthropogenic threats, notably deforestation of the drainage basin, overfishing, and climate change (Dobiesz et al., 2010).

Trophic relationships

Food preferences of the pelagic fish have been analyzed from the stomach contents of freshly caught fish (Coulter,

1991; Mannini et al., 1999). Much less is known about the trophic relationships in the lower part of the pelagic food web, but recently, the trophic relationships have been clarified using stable isotope ratios of carbon and nitrogen in different components of the food web (Sarvala et al., 2003).

Most of the phytoplankton biomass is located in the 0–40 m layer, with maxima at 0–20 m, and more rarely at 40 m. Deep chlorophyll maxima and surface “blooms” (typically of *Anabaena*) are occasionally observed, particularly in October–November (Salonen et al., 1999). Phytoplankton community comprises up to about 200 species. The phytoplankton assemblage is dominated by chlorophytes and cyanobacteria, with diatoms (such as *Nitzschia*) developing mainly in the dry season (Hecky and Kling, 1981; Vuorio et al., 2003; Cocquyt and Vyverman, 2005; Descy et al., 2005). The dominant cyanobacteria are very small unicells (picocyanobacteria, mostly *Synechococcus*), more abundant in the southern basin, whereas green algae dominate in the north end (Descy et al., 2010). Picocyanobacteria are important producers in Lake Tanganyika (Sarvala et al., 2003; Vuorio et al., 2003; Descy et al., 2005). In 2004–2007, photosynthetic picoplankton (mostly picocyanobacteria) comprised 41–99% of the total phytoplankton biomass, with highest values in the south basin in the dry season (Stenuite et al., 2009a). Heterotrophic bacteria are also important producers of biomass (Stenuite et al., 2009b). Heterotrophic nanoflagellates are abundant and diverse, and ciliates with endosymbiotic algae are abundant at times (Pirlot et al., 2005).

Multicellular zooplankton comprises one calanoid species (*Tropodiatomus simplex*), and one medium-sized and one small cyclopoid species (*Mesocyclops*

aequatorialis, *Tropocyclops tenellus*). Peculiarities of Tanganyika are several species of freshwater shrimps (from the genera *Limnocaridina* and *Macrobrachium*), and a medusa, *Limnocyclus tanganyicae* (Coulter, 1991; Kurki et al., 1999).

Advanced developmental stages of *Mesocyclops* are predatory. *Tropodiaptomus* is a herbivore, but it may feed on ciliates, too. Judging from their isotope signatures, the small cyclopoids and shrimps seem to be feeding on algae, particularly cyanobacteria (Sarvala et al., 2003). Big shrimps prey upon zooplankton. The medusae feed on crustacean zooplankton, but they may contain high densities of picocyanobacteria rendering the whole animal visibly pink in color. In adequate light, such medusae are net producers rather than consumers. The medusae have no significant predators, thus being a dead end in the food web.

Fish biology and fisheries

Lake Tanganyika is renowned for its productive pelagic fishery, which is an important source of protein for millions of people in the surrounding area. About 45,000 fishermen are directly engaged in fishing. In the 1990s, the total catches approached $200,000 \text{ t a}^{-1}$ or about $60 \text{ kg ha}^{-1} \text{ a}^{-1}$. Dried fish is sold $>1,000 \text{ km}$ away. The biological basis of the fishery was investigated in 1992–2001 in a comprehensive ecosystem study “Research for the Management of the Fisheries on Lake Tanganyika” (LTR; Mölsä et al., 1999; Mölsä et al., 2002; Sarvala et al., 1999).

There are three main types of fisheries in Lake Tanganyika: industrial purse seines, artisanal lift nets, and various traditional methods, such as scoop nets, gillnets and hook and line (Coulter, 1991). Traditional fishery yields a minor part of the total catch. Most fishing is done at night using light attraction. Major part of the catch derives from the artisanal fishery in which two clupeid species, *Stolothrissa tanganyicae* and *Limnothrissa miodon*, compose about 65% of the total. The most important species in the lift-net fishery is *Stolothrissa* (max. length 12 cm), which spends most of its life in the pelagic area, feeding mainly on copepod zooplankton and also on shrimps. *Limnothrissa* can grow to 17 cm, and feeds on copepods, shrimps, and especially on young *Stolothrissa*.

A typical industrial fishing unit consists of a purse seiner, an auxiliary vessel for the seine, and 3–4 lamp boats. At present, the industrial purse seine fishery targets mainly *Lates stappersii*, the smallest of the four endemic *Lates* (“perch”) species in Tanganyika. It can grow to 50 cm long, but a typical size in the catch is 30–35 cm. Juvenile *L. stappersii* feed on zooplankton, but with increasing size, they gradually switch to feeding on shrimps and fish, especially *Stolothrissa*. The other large *Lates* species, *L. mariae*, *L. microlepis*, and *L. angustifrons*, all potentially growing to 50–100 cm long, became sparse soon after the beginning of purse seining in the 1960s. *L. mariae* and *L. angustifrons* feed largely on benthic fish and partly on shrimps and on the

small clupeids. *L. microlepis* is a specialized predator on *Stolothrissa*.

There is an inverse correlation between the abundance of *Stolothrissa* and *L. stappersii* which is often interpreted as the consequence of predator–prey relations but may mainly reflect the underlying fluctuating limnological environment. Currently, the two species appear spatially segregated in the lake, *S. tanganyicae* dominating in the north while *L. stappersii* is generally abundant in the south where it feeds mostly on shrimps. The abundance of *S. tanganyicae* is positively correlated to plankton biomass, while water transparency, depth of mixed layer, and oxygenated water appear important drivers for the abundance of *L. stappersii* (Plisnier et al., 2009).

The fishing pressure in Lake Tanganyika has steadily increased over the last decades. In the 1990s, the total lake-wide catches of *Stolothrissa* were estimated to be about 25%, and those of *Limnothrissa* 30% of the calculated production, suggesting that the present fishery of the planktivorous clupeids is sustainable. The harvest rates of the *Lates* piscivores, in contrast, were extremely high, and excessive exploitation was likely to occur at least locally in the most intensively fished northern and southern ends of the lake (Sarvala et al., 2002; Mulimbwa, 2006). According to bioenergetic calculations, the food requirements of the planktivorous fish were a reasonable fraction, 25–38%, of the zooplankton production. In contrast, very high predation pressure was indicated on the shrimps and prey fish (Sarvala et al., 2002).

Estimates for primary production vary from 123 to $662 \text{ g C m}^{-2} \text{ a}^{-1}$ (Sarvala et al., 1999; Stenuite et al., 2007). Bacterioplankton production is about 20–25% of phytoplankton production (Sarvala et al., 1999; Stenuite et al., 2009b). Zooplankton biomass (1 g C m^{-2}) and production ($23 \text{ g C m}^{-2} \text{ a}^{-1}$) suggest that the carbon transfer efficiency from phytoplankton to zooplankton is low, in contrast to earlier speculations but in accordance with the apparent importance of the microbial food web. Planktivorous fish biomass (0.4 g C m^{-2}) and production ($1.1 \text{ g C m}^{-2} \text{ a}^{-1}$) likewise indicate a low carbon transfer efficiency from zooplankton into planktivorous fish production (Sarvala et al., 1999; Sarvala et al., 2002). Relatively low transfer efficiencies are not unexpected in a deep tropical lake because of the generally high metabolic losses due to the high temperatures and presumably high costs of predator avoidance. The total fisheries yield in Lake Tanganyika in the mid-1990s was 0.08–0.14% of pelagic primary production, i.e., within the range of typical values in lakes (Sarvala et al., 1999).

Climate change

Recently, concerns have arisen on the possible effects of climate warming on the productivity and fisheries of Tanganyika (O'Reilly et al., 2003; Verburg et al., 2003). Higher temperatures and lower wind stress could result in increased stability of the water column and sharpening of the vertical temperature gradient. The increased

stability would then diminish mixing of hypolimnetic nutrients into the euphotic zone and decrease primary productivity. There is a consensus about recent warming of Lake Tanganyika and several other East African lakes and its consequences to stratification, although the evidence is not unequivocal (Sarvala et al., 2006a; Sarvala et al., 2006b; Verburg et al., 2006). The changing climate is ultimately expected to affect the fisheries yields, but so far the observed variations in fish catches mainly reflect changes in fishing practices and short-term environmental fluctuations, not directional climate change (Sarvala et al., 2006a; Verburg et al., 2006), and even the postulated decrease in primary production is as yet uncertain (Sarvala et al., 2006b).

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THAMES WATER: DEVELOPMENT OF LONDON'S POTABLE WATER SUPPLY AND THE ROLE OF BANKSIDE STORAGE RESERVOIRS

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Historical perspective

Predecessor organizations of Thames Water could be said to date back to circa 1582, when the City Corporation granted permission to Peter Morice, a Dutchman, to lease an arch of London Bridge, where water wheels were constructed, to pump R. Thames water to local housing through a series of wood, and later, lead pipes. This system established the first water supply company in the country – the London Water Works (2005).

By the end of the sixteenth century, the population of London had swelled to approximately 180,000 residents, and London now faced an acute shortage of clean drinking water.

By the turn of the century, Edward Colthurst, a former army captain, devised plans to transfer water by gravity from springs in Hertfordshire to Islington in North London. This was to become the New River (2005).

In 1602, Colthurst received support for the project from the City Corporation, but Queen Elizabeth I was concerned that navigation in the R. Lee may suffer.

A commission was established to investigate these issues, but the Queen died before Colthurst was granted a license to start the work.

In 1604, James 1st granted permission for the work to start provided the New River was no more than 6 ft wide and the work was finished within 7 years.

By 1605, only three miles had been completed, and Colthurst required further funding from the City Corporation. The funding debate dragged on for the next 3 years, when in 1609, the Corporation accepted an offer from Hugh Myddelton to complete the work in four years.

The 40 mile New River was designed to follow the 100 ft contour from Chadwell Spring, in Hertfordshire Herts to the Round Pond at New River Head in Islington.

On Sept 29th, 1613, in the presence of local dignitaries, the New River was opened by the Lord Mayor of London, and the New River Water Company was established.

Fresh water could now be supplied to local residents via a series of fifty eight water mains made from elm tree trunks. One-inch bore lead pipes delivered water to those customers who could afford to pay for the service.

During the eighteenth and nineteenth century, various developments in London's water supply were affected including the construction of an Upper Pond at the New River Head, straightening the course of the New River, and the establishment of eight water companies supplying the Metropolitan area, namely:

Company	Date founded
The New River Company	1619
The Chelsea Waterworks Company	1723
The West Middlesex Waterworks Company	1806
The East London Waterworks Company	1807
The Grand Junction Waterworks Company	1811
The Lambeth Waterworks Company	1785
The Kent Waterworks Company	1809
The Southwark and Vauxhall Waterworks Company	1760

However, concerns about the purity of water were raised after a further outbreak of cholera in 1849 when Dr. John Snow famously determined the causal link between contaminated water and water-related disease, originating from the Broad St. well in Soho. As a consequence, water companies were required to meet new statutory demands, and in 1852, the Metropolis Water Act was established.

The Act determined that all water companies must abstract R. Thames water above Teddington weir (the tidal limit), that all river water must be filtered, and all filtered water must be stored in covered reservoirs.

In 1871, revisions of the Metropolis Water Act determined that water supplies were to be constant, domestic plumbing standards were implemented, and the first "water examiner" was appointed.

In 1904, the Metropolitan Water Board (MWB) was established which took over the responsibilities for water

supply from all the previous water companies. Ten years later, the MWB built its new headquarters on the site of the Round Pond in Islington. It was named New River Head.

Prior to the establishment of the MWB, a number of the previous water companies had erected river water pumping stations in the Lower Thames and Lee Valleys. They were located above the tidal limits of both rivers and designed to pump to a series of small bankside storage reservoirs which had been constructed upstream of the associated water treatment works.

The reservoirs were commonly named after the individual companies, and some are still in operation in the twenty-first century.

For example, at Hampton WTWs, in the Lower Thames Valley, one of the earliest reservoirs built is still in use as a balancing tank at the head of the water treatment works. This "reservoir," built in 1879, was named the Grand Junction reservoir after the original water company. Close by are the redundant Stain Hill reservoirs, constructed in 1898.

Further, to the west, at Kempton Park WTW's, two additional reservoirs were constructed in 1906, namely, the Kempton Park East and West reservoirs.

South of the R. Thames at the Walton on Thames treatment works are four reservoirs which were constructed by the Chelsea Water Company in 1877. Next to them are the four Lambeth Water Company reservoirs, two of which were built in 1874 and the others in 1901 and 1903.

These small reservoirs are now redundant, and following a period of major gravel abstraction, the area will be converted to a wildlife and wetlands nature reserve.

Between 1863 and 1903, in the Lee Valley area, NE London, 11 small storage reservoirs were constructed (details in Table 2, below). They are all in operational use today, either as water supply reservoirs or as sedimentation basins for wash water originating from the Coppermills WTWs.

After 1904, the management of the reservoir complex became the responsibility of the Metropolitan Water Board. The MWB inherited a combined storage volume in the Thames Valley of $196 \times 10^6 \text{ m}^3$.

The 1973 Water Act simplified the way that water and wastewater services were provided in the UK and paved the way for the creation of ten major Water Authorities in 1974.

By the time the Thames Water Authority had replaced the MWB, the ongoing reservoir storage strategy had ensured an additional storage capacity of $150 \times 10^6 \text{ m}^3$, equivalent to approx. 100 days supply to Greater London.

Of the 25 reservoirs originally adopted in 1974, ten strategic reservoirs in the Lower Thames Valley area are those primarily considered in any management decision process.

These ten reservoirs provide a total storage volume of $165.1 \times 10^6 \text{ m}^3$, five of which are of prime importance for water resources in that they contain, individually, more than $19 \times 10^6 \text{ m}^3$ and comprise 82.5% of the total Lower Thames Valley storage volume.

In 1989, a revision of the UK Water Act enabled parts of the UK water industry to be passed to the private sector.

The newly formed Thames Water plc took responsibility for providing water and wastewater services to London and the Thames Valley area in SE England.

Table 1 below lists the major reservoirs located in the Thames and Lee Valleys.

By 2001, Thames Water plc was acquired by the international multi-utility, the RWE Group, with Thames Water becoming RWE's Water Division. Thames Water Utilities Limited (as part of Thames Water plc) is now owned by Kemble Water Holdings Limited (Kemble Water) which acquired Thames Water from RWE in December 2006.

To date, Thames Water, UK, currently supplies clean water services to 8.7 million customers, (2,800 million l/day) from 103 water treatment works through 31,000 km of water mains. Wastewater services are provided to 13.8 million customers via 65,151 km of sewers at 351 sewage treatment works. Where applicable, advanced water treatment processes have been incorporated within the existing treatment works. These additional processes include the use of ozone and granular activated carbon treatment to assure compliance with the exacting pesticide regulations and phosphoric acid dosing facilities to assure lead compliance at customer's taps.

13,100 km², comprising a varied mixture of urban and rural development. Each river system receives runoff from lowland agricultural land and a significant number of sewage treatment works. The characteristics of the river sources are typical for those of a lowland river in a temperate zone (Toms, 1987).

Previous management strategies suggested that the R. Lee and groundwater sources were at their maximum for exploitation and any shortfalls would be met by increased abstraction from the Thames Valley basin.

However, over the past decade, with the impact of climate change, i.e., longer drier summers and shorter wetter winters, has resulted, on occasions, in a negative supply/demand balance for London. As a consequence, a number of strategies have been developed to stay ahead of the rising demand for water. These include the resurrection of some redundant aquifer sources, exploitation of new aquifer sources, further development of the aquifer storage and retrieval system, by 2007, the operation of a desalination plant located on the north bank of the Thames estuary at Beckton, and possibly, by 2020, a new bankside storage/river-regulating reservoir located in the Upper Thames area of Oxfordshire.

The role of bankside storage reservoirs

Introduction

Approximately 70% of London's water supply is sourced from the River Thames; 15% sourced from the River Lee and the remainder from boreholes in the surrounding chalk aquifers. The total catchment area is approximately

Characteristics of the surface water sources

All the exploited river sources can be described as eutrophic, with nutrient concentrations of approximately 0.5–1.5 mg PO₄-P l⁻¹, 5–15 mg NO₃-N l⁻¹, and up to 20 mg SiO₂ l⁻¹.

Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Table 1 Major reservoirs located in the Thames and Lee Valleys

Thames Valley reservoirs	Date completed	Depth, m	Area, Ha	Volume, 10 ⁶ m ³	Mixing method
Staines, north	1902	8.0	72.0	7.2	Air domes
Staines, south	1902	10.5	99.6	7.95	Air domes
Knight	1906	11.6	20.8	2.1	None
Bessborough	1907	11.6	29.9	3.1	None
Island Barn	1911	8.2	49.0	3.7	None
Queen Mary	1925	11.5	286.3	30.4	None
King George VI	1947	16.0	141.6	20.3	Air domes
Queen Elizabeth II	1962	17.2	128.3	19.6	Angled jets
Wraysbury	1971	21.5	202.3	34.5	Angled jets
Queen Mother	1974	25.0	192.2	38.0	Angled jets
Lee Valley reservoirs					
Walthamstow no. 1	1863	3.0	7.7	0.11	None
Walthamstow no. 2	1863	3.0	5.3	0.08	None
Walthamstow no. 3	1863	3.0	4.9	0.07	None
Walthamstow no. 4	1866	5.8	12.1	0.38	None
Walthamstow no. 5	1866	5.8	16.6	0.52	None
Low Maynard	1870	3.0	10.1	0.15	None
High Maynard	1870	5.8	15.4	0.48	None
East Warwick	1897	5.8	17.4	0.55	None
West Warwick	1897	5.8	13.8	0.43	None
Banbury	1903	8.5	36.8	2.8	None
Lockwood	1903	10.4	30.0	2.2	Sparge pipe
King George V, N&S	1914	8.9	172	12.4	Sparge pipe
William Girling	1951	12.5	135	15.8	Jets/sparge pipe

During periods of mod-high flow, the river can also contain high organic carbon and silt loadings, ranging between 0.5 and 6.0 g C·m³, and turbidity values ranging from 10 to 100 NTU.

The river systems can also support a range of microbiological and algal species at varying concentrations dependant on the rainfall values, flow conditions, and season impacts. In spring and summer when flows are lower, the river can be highly productive with phytoplankton biomasses values in excess of 200 mg-Chla/m³ recorded, the dominant algal species generally the centric diatom, *Stephanodiscus hantzschii*.

Reservoir classification, morphology, and management

As illustrated in Table 1, the principle Thames Valley and Lee Valley storage reservoirs were constructed between the period 1951–1974, resulting in a doubling of the total storage capacity from approx. 100–200 Mm³ (Steel, 1975).

The reservoirs can be classified as eutrophic bankside storage reservoirs or pump-storage embanked reservoirs, as opposed to a dammed valley type reservoirs.

Good examples of this mode of construction are the Wraysbury reservoir near Staines, Middx, and the Queen Elizabeth II reservoir, West Molesey, Surrey.

Overlain by drift sediments and river gravel, the underlying geological formation of the Thames Valley consists of a layer of largely impermeable clay. The clay layer forms the base of the reservoir. An impermeable clay core is supported both inside and out by an earthwork embankment constructed from the gravel and ballast mined from the reservoir basin (Bayley, 1998).

The internal embankment is lined with concrete to prevent wave erosion with a wave wall to prevent overtopping. The external embankment is grassed over, and maintained by sheep grazing. The puddled clay internal core is keyed into the underlying clay layer to form a watertight seal. As the structure is built up from ground level, all the water entering such reservoirs has to be pumped from the river source, in this case the R. Thames or R. Lee.

In some of the older reservoirs, significant quantities of gravel were left on the reservoir floors. In selected reservoirs, the alluvial gravels are being dredged out and processed for use in the building industry or for highway construction.

All Thames Water reservoirs have similar, simple morphologies, with steep internal sides lined with concrete, and a relatively uniform depth. They are operated with known quantities of throughput water with the aspiration to maintain a uniform mixed depth when in supply. Retention times can range from 10 to 100 days.

The current reservoir management strategy, as per the best operating practice document, does not regard each reservoir in isolation. Water operations now recognized that the reservoir complex is an integral part of the overall water supply chain. The system not only enables provision

of a reliable water source during drought periods but also provides an important first treatment stage in the water supply process.

In addition, the reservoirs also act as a safeguard when point source pollution events occur in the rivers. Thames Water and the Environment Agency have linkages with their continuous river water quality monitoring stations via a series of control rooms. In the event of a gross pollution, one management option is the closure of intakes for an extended period thereby safeguarding supplies of water to London.

Of interest, it was Frankland who, in 1894, identified that storage of polluted river water for periods of 2–3 weeks can result in a significant reduction in concentration of intestinal bacteria with virtual elimination of pathogenic species and reduction in turbidity. The current operational retention periods account for this natural reduction and are contributory to ensuring that the silt and microbiological loadings onto the receiving water treatment works are minimized (Ridley and Steel, 1975).

During the early period of reservoir construction, designers tended to ignore the ecological importance of the depth volume ratio of the water mass. Hence, the early reservoirs were constructed as shallow impoundments (<10 m depth) with a large surface area as opposed to a “modern” reservoir with depths up to 25 m and requiring less land area (<200 ha).

In temperate climates, the water column of a shallow basin is likely to be well mixed for most of the year, whereas deeper basins have a propensity to thermally stratify during the summer months. Therefore, the depth of the water relative to the surface area will have a significant impact on the overall environmental status of an individual reservoir and influence biological productivity.

During the period 1926–1950, reservoir source selection and management options were limited. The available reservoirs often supported large crops of diatoms and blue-green algae, which, on occasion, severely constrained the associated water treatment processes and often limited supply (Steel, 1975).

Various attempts at algal control in Queen Mary reservoir were undertaken including mass dosing of copper sulfate (up to 1 mg/l Cu), low-level continuous dosing of between 0.1 and 0.3 mg/l Cu, or closure and switching to an alternative source.

However, the alternative source generally the KG V1 reservoir was regularly subject to a stable thermal stratification phenomenon.

Thermal stratification may occur on any large, deep lake or reservoir in temperate climates. Generally, the surface area has to exceed 1 km² and with depth exceeding 10 m. Stratification on smaller, shallower water bodies tends to be localized and transient.

There are two periods in the year when thermal stratification can occur: winter and spring. The main thermal stratification impact is likely during spring, while an inverse stratification may occur in winter if ambient

temperatures are low for an extended period, then the reservoirs can ice over.

Reservoirs that stratify once a year are termed "monomictic," while those that regularly stratify twice a year are termed "dimictic."

Thermal stratification of a water body results because water has a maximum density at 4 °C and that water has a high specific heat (approximately $4.2 \text{ J.g}^{-1}.\text{°C}^{-1}$). During spring and early summer, the upper layers of the water column are warmed and, as a result, become less dense. Gradually, a distinct layered structure develops in the water column with a warm top layer, a cold denser deep layer with a dividing region between these layers called the thermocline, characterized by a temperature change of 1.0 or more degrees Celsius per meter depth.

The warm upper layer is known as the epilimnion and the cold dense layer, the hypolimnion. The thermocline acts as an almost frictionless layer and also forms as an effective barrier to rapid diffusion of chemical species. In deep basins, this thermal stratification is stable due to the low center of gravity of the water column.

Algal growth under these conditions can only take place where there is sufficient light for photosynthesis. The algal populations may grow until limited by the available light (self shading) or other ecological factors such as grazing by zooplankton and the impact of high fish biomasses.

As the available light energy reduces exponentially with depth, then the euphotic depth (m) is defined as the depth at which useful light or "photosynthetic active radiation" (PhAR) can penetrate.

The rate at which light is adsorbed with respect to depth is known as the extinction coefficient (m^{-1}).

Unmixed, stratified basins tend to have small extinction coefficients with large euphotic depths. Hence, in a stratified system, algal growth will be confined to the epilimnion dependant on the epilimnion depth and the euphotic depth, and because any algal growth is not limited by nutrient availability, significant algal populations may develop. Hence, the epilimnion water will become difficult and expensive to treat.

In addition, any dead and decaying algae will sediment through the depths and enter the hypolimnion. As there is insufficient light at these depths to sustain further algal growth, they intern will die. At first, decomposition of the algae can take place relatively rapidly while dissolved oxygen levels remain high, but eventually, the decomposition processes will remove all the oxygen from the hypolimnion, exacerbated by the thermocline acting as an effective barrier to oxygen diffusion from the epilimnion.

At this stage, bacterial species can utilize dissolved nitrate and reduce any nitrate to ammonia. The anaerobic processes will then continue to utilize any insoluble manganese (II) and iron (II) compounds present with eventual reduction of sulfates to either sulfide or elemental sulfur.

At this stage, the hypolimnion water is likely to be black in color and smell of rotten eggs. If light can

penetrate through to the hypolimnion, the water may have a purplish-pink color (due to particular species of bacteria) though still having a foul, rotten egg odor.

Thus, a stratified reservoir can contain water that is virtually untreatable due to low dissolved oxygen concentrations, high ammonia and/or sulfide compounds, i.e., the hypolimnion, or difficult and expensive to treat due to high algal biomass values, i.e., the epilimnion.

Under these conditions and if a seiche is present, i.e., an internal oscillation of the thermocline, then a reservoir outlet with specific depth drawoffs may experience periodic epilimnetic and hypolimnetic water during the course of a few hours or days. Oscillations of 4 m amplitude have been recorded within the Thames Water, KGV1 reservoir.

Studies by White et al. (1955) suggested that thermal stratification could be controlled by internal mixing using submerged jets. Their studies were fundamental in the design of subsequent reservoirs and were incorporated within the Queen Elizabeth II reservoir built in 1962 (White et al., 1955).

Further developments in hydrobiology research have contributed to a greater understanding of the physico-chemical and biological interactions that occur within the storage reservoirs. It is now recognized that mixing and manipulation of deep pumped storage reservoirs can have a significant impact on the ecology of the basins. All subsequent Thames Water storage reservoirs have had jet mixing systems incorporated within their design.

The design of the inlet and outlet structures has also progressed from simple shoreline inlets and outlets to modern inlet piers with a selection of low-velocity inlets and high-velocity angled jets and centrally located wet tower outlets with multiple drawoff levels.

Note that inlet jetted systems can only operate when abstracting from the river, so if abstraction is curtailed, internal recirculation pumps are available to maintain a mixed basin.

When operationally feasible, some of the older reservoirs (constructed pre-1962) have had internal air mixing systems installed, using either a series of air diffusers or sparge pipe systems.

Algal biomass manipulation

In addition to securing stored water resources, another primary objective of reservoir management is to supply stored water to the receiving works with minimal presence of biological particles, i.e., algae.

As previously stated, the inbuilt mixing mechanisms are designed primarily to minimize the impact of thermal stratification. However, an additional component is the successful manipulation of the phytoplankton biomass with important benefits for water treatment works process control, cost efficiencies, and security of supply.

For each reservoir, there is a theoretical minimum retention period, when all the river-derived algae should have died off and limited lacustrine algae will develop.

Minimum retention periods of 5–10 days are often quoted, but as the reservoirs have been designed to

provide between 30 and 100 days storage, these values are impractical to achieve.

Under the current mode of operation, the lacustrine algae have the potential to achieve their theoretical growth maxima, hence the development of low-cost engineering solutions (jet mixing/aeration mixing) to improve circulation in deep basins, minimize the impact of thermal stratification, and concurrently influence phytoplankton productivity.

Modern computational fluid dynamic (CFD) techniques can now be applied to understand the flow characteristics of each reservoir under varying inlet and outlet configurations.

As previously stated, in the Thames Valley reservoirs, nutrient concentrations are high, and the water is classified as eutrophic. Simplistically, this means that algal growth is unrestricted by available nutrients.

In reality, the algal taxa have different requirements for the major nutrient elements and micronutrients. All algae require phosphorus in a suitable form, and most taxa require an inorganic nitrogen source.

The majority of Cyanobacteria ("blue-green algae") are able to fix atmospheric nitrogen. Diatoms typically require dissolved silicates to form their frustules. In the UK, micronutrients (e.g., boron, molybdenum) are not usually limiting.

Within the Thames Valley reservoirs, the nutrient concentrations are over two orders of magnitude greater than that required for maximal algal growth.

In addition, recognition that certain species of algae may form a potential threat to human health in the form of toxins will influence the management of the reservoir complex.

In marine environments, the most notable events often involve the paralytic poisoning of shellfish from marine dinoflagellates (Bayley, 1998).

Within freshwater ecosystems, the most recent concerns have involved some genera of Cyanobacteria. The toxins produced have been classified into three main groups: the hepatotoxins, the neurotoxins, and polysaccharide complexes.

Recent work has concentrated on the most common hepatotoxin, microcystin-LR and, to a much lesser extent, the neurotoxin anatoxin-a. The risk to health is believed to be mainly from ingestion of the cells themselves, and a relatively large dose is required to have an impact on human health.

Filtration and other treatments (use of ozone and carbon adsorption) are effective at removal of these cells and toxins. The greatest risk is when people consume contaminated water with little or no treatment or participating in water sport activities where decaying blue-green algae scum is present.

Thames Water and the UK Environment Agency have a requirement to be aware of the potential of the reservoirs to support toxic blooms of Cyanobacteria.

Advice and guidance is delivered to all operatives and those who take part in water-based recreational activities.

Large populations of algae are also undesirable in terms of both aesthetic parameters and potable water treatment costs. Under certain conditions, undesirable taste and odors can be produced by many species of algae. The most common chemical compounds responsible for bad taste and odor are 2-methylisoborneol (MIB) and geosmin. One algal species, *Synura petersenii*, produces two compounds causing tastes of "cucumber" and "fish" at very low cell densities.

In terms of the water supply production, the most problematic issue associated with algae is the potential to increase treatment costs and a possible reduction in work output.

Compliance with the UK Water Supply Regulations 2000 and the TW Best Operational Practice documents requires that water be treated to remove algae and other contaminants.

Such treatments are very effective but can become overwhelmed by large communities of algae.

While there is no direct risk to health, occasionally, the volumetric output of treatment works can be severely constrained, and treatment costs increased. Thames Water has recognized these issues and routinely monitors the water quality status at all stages of the treatment process. The data set is used to produce short-term forecasts of expected changes in water quality and for use in new works or reservoir design programs.

Within a "managed" basin, i.e., one where a variety of reservoir management tools are available to influence the flow characteristics of the reservoir and low-velocity inlets, combinations of varying angled jet inlets (0°, 22.5°, and 45° to the horizontal) and internal recirculation pumps have been incorporated within the designs.

The current mode of operation determines that during the autumn/winter period, the river water is abstracted through the low-velocity inlets. Prevailing climatic conditions ensure that the temperature profile is homogeneous, hence no requirement to "jet" mix. Operation of these units also promotes sedimentation of the river derived inorganic silt. Accumulation rates of allochthonous and autochthonous material have been estimated between 5 and 10 mm per year, depending whether the reservoir is operated as a continuous throughput basin or a standing reserve.

The problems associated with thermal stratification can mean that the capacity of a reservoir is not always available for use when required. Up to the middle of this century, reservoirs in the London area were built fairly shallow, and thermal stratification was uncommon. The demand for more water resources, however, meant that larger, deeper reservoirs were required. As a result, trials of various artificial mixing devices were initiated.

They included:

1. Floating recirculation pumps delivering hypolimnion water to the epilimnion
2. Jet mixing through narrow inlet jets located on the reservoir floor with entrainment of the water mass in the jet plume

3. Diffused air mixing where compressed air is blown into the reservoir through a series of diffuser heads

Of the various trials undertaken, jet mixing was selected as the standard design for Thames Water's de-stratification strategy. These devices were added to the newer, deeper basins during construction (Ridley et al., 1966).

Further studies have indicated that jet angles between 0° and 15° would be preferable.

Also note that jet mixing can increase pumping costs by 2–3%.

The jets themselves do not mix the reservoir directly as the velocities and energy involved will be insufficient. River water temperatures are generally greater than those in the reservoir, and this temperature differential assists jet-induced mixing. The jet of water entering the water body at high velocity entrains a relatively large volume of reservoir water. The magnitude of the water masses is of such stature so as to be influenced by the Coriolis effect of the earth's rotation and when prevailing wind direction is taken into account, full-depth mixing of the large basins has been achieved within 48–72 h at little extra cost. At the outlet, the drawoff levels can be altered to take advantage of differences of quality through the depths.

If the jets are started when a temperature differential is first recorded (generally 2°C , top–bottom), then thermal stratification can be controlled. The jets are normally turned off when temperatures start to fall at the end of the summer months.

Figure 1 illustrates one-half of the inlet jet configuration of Wraysbury reservoir, in operation since 1971.

Diffused air mixing for algal control

During the 1970s, it was decided to attempt to de-stratify some of the older reservoirs (depth range of 8–16 m) using diffused air mixing. Retrofitting jetted inlets was deemed uneconomic and involved draining the reservoirs with associated major civil engineering works. A number of devices were investigated with diffused air bubble plume mixing selected as the practical and cost-effective method. The procedure is relatively simple and described in detail by Goosens (1979).

Similar systems have been successfully deployed in the Netherlands within the Biesboch water storage scheme (Oskham, 1983).

To date, diffused air mixing through point source diffusers has been installed within the KGV1 and Staines north and south reservoirs in the Thames Valley and a perforated pipe system in the Lockwood and William Girling reservoirs in the Lee Valley area.

Mixing efficiency is determined by the degree of stratification, epilimnion thickness, injection depth, and the number of injection points.

For effective operation, a series of diffuser heads ($3 \times$ sets of 6) were placed some 2 m below the floor of the reservoir and supplied with up to $0.3 \text{ m}^3/\text{s}$ with oil-free air, which will lift approximately $50 \text{ m}^3/\text{s}$ of water to the surface. Figure 2 illustrates one set of diffuser heads within



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 1 Wraysbury reservoir inlet jets showing different angles from the horizontal.



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 2 Air mixing diffuser blocks located within KGV1 reservoir, Thames Valley.

KGV1 reservoir installed in the 1980s, in dry conditions coinciding when the reservoir was drained for operational purposes.

The diffusers used include sets of ceramic domes, more usually used for sewage works activated sludge plants and purpose built foam rubber blocks. More recently, porous flexible hose has been used. Air mixing does not significantly aerate the water directly, but each bubble acts as a lift mechanism thus transferring water from the lower layers to the surface. A bubble plume with entrained water rises to the surface where mixing takes place below and

within a visible "boil." Water to air movement ratios have been estimated to be in the order 1:240.

The prolonged drought of 2005–2006 which affected Southeast England significantly reduced river flows and available volumes for abstraction.

By early 2006, it was apparent that if the predicted hot and dry period continued into the summer, then reduce treatable reservoir volumes would be limited by reduced or no abstraction thus negating any inlet jet mixing. The impact would be the potential for stable thermal stratification, a resultant deterioration in water quality with

excessive algal growths, etc. As a result, an internal emergency drought scheme was implemented to preserve the treatable volumes held within four major reservoirs in the Thames and Lee Valleys to assure the security of drinking water supply to London.

The design an air mixing system suitable for large open reservoirs was based on the paper by L Goosens (Delft University Press) "Reservoir Destratification with Bubble Columns" which describes a design for an unconfined diffused air mixing system.

A number of factors were important:

- For each level stratification and water depth, there is an optimum air flow rate.
- Air needs to be introduced at depth (i.e., the lowest points on the reservoir floor). This factor indicated that an air mixing system would be more effective in deeper reservoirs.
- The air needs to be in the form of small bubbles and released at a calculated number of diffusing points in the reservoir (three to four per reservoir).
- The rising vertical pattern of the plume would raise the bottom water to the top of the reservoir and induce mixing with the warmer layers.
- Each air system needed to be arranged with spare capacity and adjustment to enable the flow rate to be varied to accommodate seasonal reservoir temperature differences.
- The number of diffusion points and air flow rates had to be evaluated for each individual reservoir.
- Temperature gradient top to bottom and required homogenizing time.
- Ambient air temperature and humidity.

The reservoirs chosen for installation of a new air mixing system were the larger and deeper reservoirs, namely Queen Mother, Wraysbury, Queen Elisabeth II, and William Girling. The size and depth of these reservoirs are as follows:

	Max depth (m)	Max usable volume (megaliters)
Queen Mother	25.9	38,000
Wraysbury	21.39	33,874
Queen Elisabeth II	17.83	19,623
William Girling	12.5	16,511

The concept of air diffusion is common in the aeration lanes of a sewage treatment works but not at considerable depth (>20 m) at the bottom of a reservoir. The only type of known diffuser considered suitable for the application to create the fine bubbles required for the air mixing system was the *Sanitaire* Fine Bubble Membrane Tube (see Figure 3).

This type of diffuser was designed for use at relatively shallow depths (down to 5 m), and it was suggested that there may be a potential weakness in the tube construction if exposed to the higher pressures at greater depth. Factory checks by the manufacturer in a pressure chamber confirmed the suitability of the *Sanitaire* units at the higher pressures. For each diffusion point in the reservoir, a grid of 32 *Sanitaire* diffuser tubes was provided to give the required air flow.

The air requirements for mixing of the reservoirs were calculated and specified as follows:



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 3 *Sanitaire* diffuser platform (half section shown).

Queen Mother reservoir – 0.191 m³/s free air delivered (FAD) at a nominal 35.6 m H₂O to four off-delivery points

Wraysbury reservoir – 0.197 m³/s FAD at a nominal 36.1 m H₂O to a four-point delivery system

Queen Elizabeth II reservoir – 0.165 m³/s FAD at a nominal 36.4 m H₂O to a three-point delivery system

William Girling – 0.151 m³/sec FAD at a nominal 36.4 m H₂O to a three-point delivery system

Each air system was arranged with spare capacity and adjustment facilities to enable the flow rate to be varied to accommodate seasonal reservoir temperature differences.

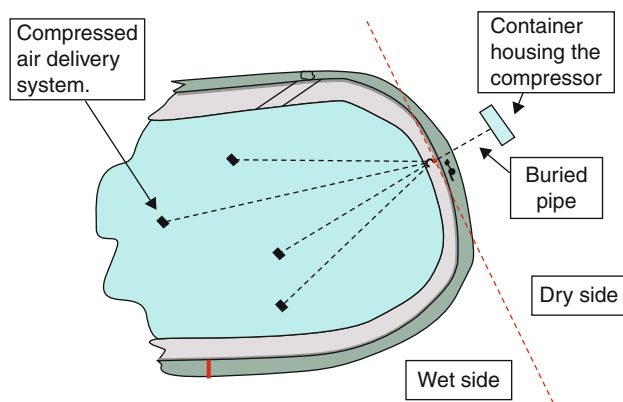
Air was provided using shore-based compressor systems installed within containers together with long (1.0–1.3 km) air delivery lines routed up and over the reservoir embankment and long submerged lengths on the reservoir bed to each diffuser platform.

The compressors operate at a higher pressure than the nominal calculated delivery pressure to the reservoir in order to provide a differential across a regulating valve. The flow capacity of the compressor was also approximately 20% oversized to allow for seasonal adjustment of air flow rates (Figure 4).

Installation method

The wet side installation involved the development novel techniques for floating out and sinking long pipelines and aeration platforms in a controlled fashion to precise locations on the reservoir floor. A marine installation contractor (Ocean Team 2000) was appointed for installation of wet side elements, and Costain acted as main contractor for the whole project. Installation methods were developed in liaison with the contractor. Important aspects are as follows:

- Bathymetric surveys were carried out over the whole reservoir area to ascertain the bottom topography and



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 4 Typical diffuser layout in reservoir.

determine the most suitable low points on the reservoir floor (for diffuser location) and to ascertain the depth of silt.

- The proposed positions for the diffuser platforms and alignments for the submerged pipelines were selected to ensure that the area of the reservoir bed for the diffuser platform is level and that there are no significant underwater valleys, slopes, high points, etc., along the pipeline route that might result in excessive pipeline strain.
- The diffuser platforms are made in two sections to allow road transportation. They are fabricated using stainless steel rolled rectangular hollow sections and shall be structurally robust as separate sections and conjoined. The arrangement allows removal and replacement of individual diffusers.
- The design of the diffuser platform allows for future recovery to maintain/replace diffusers and the like. A non-return valve and release coupling have been incorporated to prevent water entering the air line when detached from the platform.
- The diffuser platform has negative buoyancy, but the polythene air pipeline required weighting to achieve submergence in the reservoir. This was achieved using a weighting cable clipped to the pipeline along its length.
- A team of divers was used for the installation together with a fully equipped diver support boat (RIB).
- The diffuser platform positions were inspected by divers to check for suitability.
- Both platform and pipeline were supported initially by buoys and the assembly drawn out into the reservoir using the RIB until above the diffuser position and air line route.
- Working from the shore, the buoys were cut from the air line progressively and the settlement of the air line onto the reservoir floor checked using divers. This was continued over 1 km or so length of pipeline to the diffuser platform.
- A line with a string of buoys was used to stabilize the descent of the diffuser platform. Buoys cut from the platform caused the latter to sink, but this submerged additional buoys on the string which provided a controlled rate of descent. When recovering the platform in the future, it is envisaged parachute bags will be required to give a controlled rate of ascent. Buoys would expand as depth reduces caused ascent to accelerate.
- The positioning of the platform on the reservoir floor was checked by divers.
- The installed positions of the diffuser platform and submerged pipeline positions were recorded to enable future recovery/maintenance. A post-installation bathymetric survey for each reservoir was undertaken to record the diffuser platform and air line positions.

The installation as a whole over four reservoirs comprised approximately 15 km of MDPE pipeline and

3–4 aeration platforms per reservoir. Four hundred and forty-eight diffuser heads were shipped from Spain, three compressors were shipped from Germany, over 15 km of pipe work was installed both under water and within the reservoir earth wall, and 225 kW of power was secured and installed across the sites during the delivery of this project.

The first of the four reservoir mixing systems was completed and commissioned just after a period of hot weather in early June 2006. This provided an opportunity to test and prove the effectiveness of the system and whether the design brief was appropriate.

The project also incorporated the installation of a depth profile samplers, one of which was located at a limnological tower within the Queen Mother reservoir. These units enable the collection and recording of real time of vertical water quality criteria every meter depth. The quality sonde is able to record temperature, dissolved oxygen, conductivity, pH, turbidity, chlorophyll a, and phycocyanin.

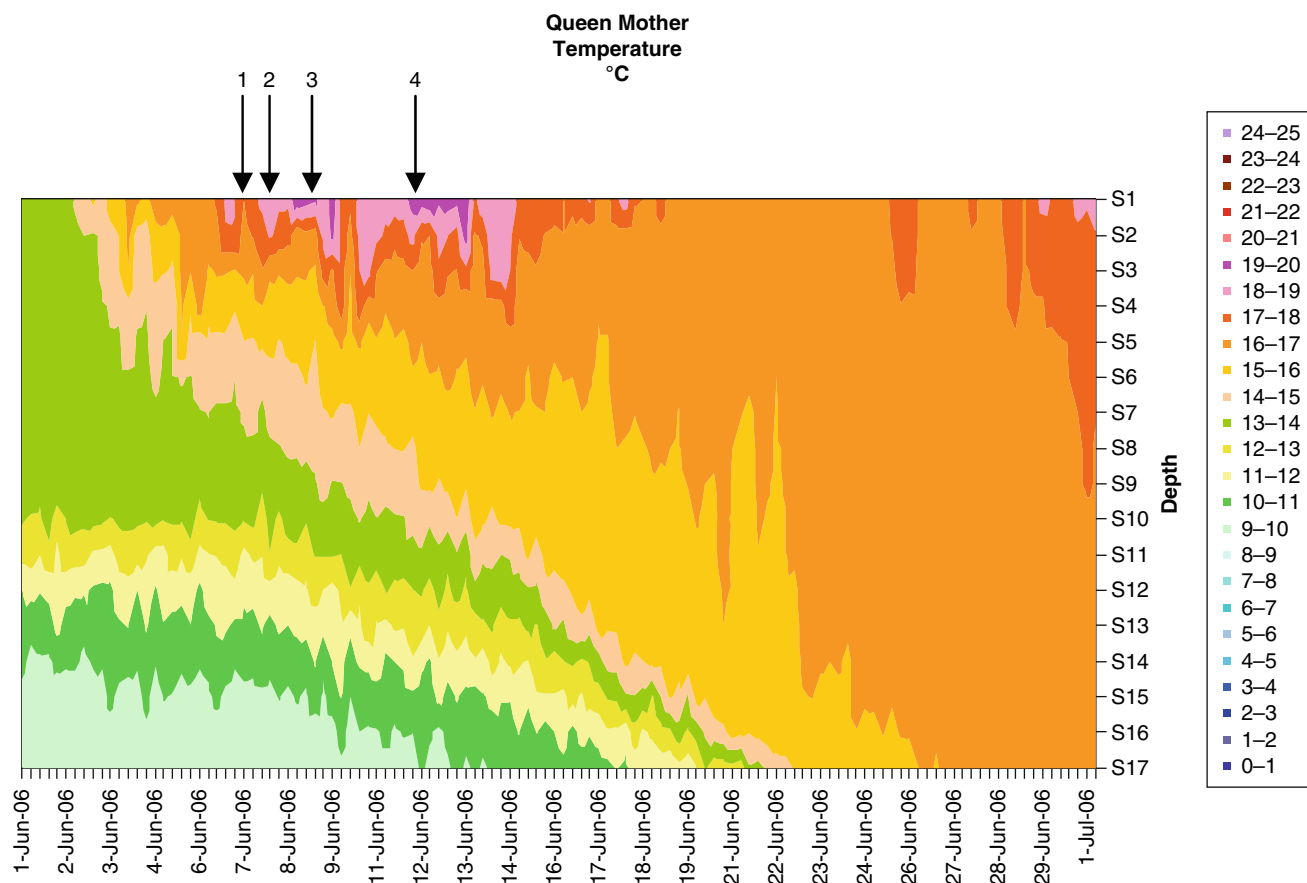
Figure 5 illustrates the resultant temperature profiles recorded and demonstrates the impact of the mixing

system as each successive aeration dome unit was “switched on.”

Prior to June 7, 2006, before the mixing system was started, the reservoir was thermally stratified with the thermocline developing at approx. 10 m. The progressive de-stratification impact to isothermal conditions as each diffuser dome was operated is ably demonstrated, and by June 24, the reservoir was fully mixed.

Pending operational demands, some reservoirs will not be required for supply purposes and revert to a standing reserve, i.e., no input or output. Under this circumstance, if mixing is not maintained and pending on the season, thermal stratification may occur. Recirculating pumps have been installed specifically for the purpose and operated to minimize stratification impacts. Such recirculation has an associated cost but is outweighed by the advantages of maintaining the resource capability and treatability.

The flexible reservoir management philosophy adopted is a balance between the requirements of water supply, seasonal loadings, operational catchment status, operational costs, and resources.



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 5 Queen Mother reservoir, 2006 – temperature isotherms profiles.

The impact of artificial mixing on phytoplankton growth

As previously suggested, a significant benefit of artificially mixing deep reservoirs is a significant reduction in algal population growth.

Within an efficiently mixed reservoir, the mixed depth will equate to the total depth of the reservoir and provide the correct mixing regime and is maintained with the mixed depth several times the euphotic depth; then, any phytoplankton populations will spend a greater proportion of their time in low-light conditions. The carbon loss from respiration is then greater or equal to the carbon gain from photosynthesis with a net effect of an overall reduction in growth rate and lower algal populations.

In addition, light energy reduces exponentially with increasing linear depth (note that not all light is useful to algae – the useful light is described as photosynthetic available radiation or PhAR).

The rate at which light is absorbed with respect to depth is called the extinction coefficient (a function of the Beer–Lambert law).

If PhAR is able to extend to the floor of the reservoir, then algal growth will not be limited until the algae “self-shade,” i.e., until the algal cells near the surface shade-out the ones below, i.e., the algae then are light limited.

In deep reservoirs where PhAR is absorbed near the surface, algal growth will be concentrated in the upper layers. This zone is called the euphotic zone, and the depth at which any further algal growth is inhibited is the extinction depth.

Note that all phytoplankton require a minimum quantity of light to survive, grow, and reproduce.

In deeper reservoirs, algal growth is restricted to a zone where there is sufficient light; this zone forms a relatively shallow layer near the water surface, between 8 and 10 m.

The use of artificial mixing devices can prevent any thermal stratification impact, and as a result, particles, including algae, will be mixed throughout the water column, so in deep reservoirs, the algae will be removed from the euphotic zone as they are circulated into the lower depths, hence limiting the algal growth as the quantity of PhAR will be effectively reduced. The effect can be compared to reducing the photoperiod, i.e., day length. Therefore, deeper reservoirs will have a larger extinction coefficient and a greater potential to reduce algal growth.

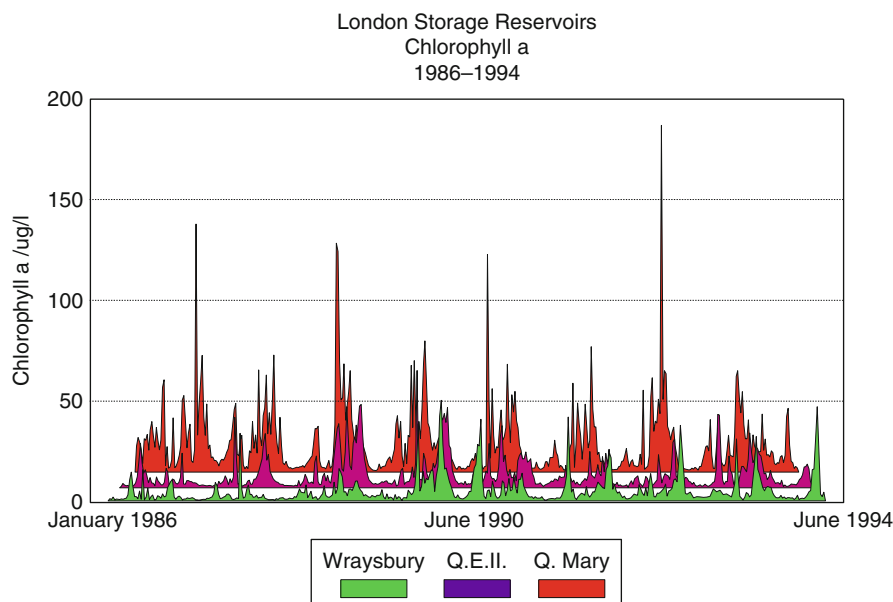
In summary

Algal growth and algal population density are reduced if the reservoir (mixed) depth is several times the euphotic depth. The effective reduction in available light energy delays the start, magnitude, and duration of any algal populations.

Figure 6 below illustrates the variation in algal growth within three Thames Valley reservoirs.

1. Queen Mary reservoir – shallow (11 m) and is not artificially mixed – algal growth is high with considerable chlorophyll *a* values.
2. Queen Elisabeth II and Wraysbury reservoirs are both artificially mixed using inlet jets. The depths for these two reservoirs are 17.2 and 21.5 m, respectively.

In general, algal control is good with Wraysbury reservoir having the lowest chlorophyll values.



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 6 Variation in algal growth within three London reservoirs, 1986–1994.

Other aspects of reservoir management

The structural characteristics and operation in the storage reservoirs make them ideal candidates for ecological modeling. Steel (1972) developed the original Talling model (1957a) to establish that for diatoms in a mixed deep basin:

- Algal growths start later
- The growth rate is constrained
- The maximum biomass is light energy limited and not nutrient limited

From Steel and Duncan (1999), it is recognized that the development and application of ecological and environmental knowledge for algal control within the Thames Water reservoirs is a complex and iterative process.

In addition to the use of full-depth mixing, which Duncan (1990) described as a “bio-manipulation technique,” the use of ecological manipulations or other bio-manipulation techniques could also offer real benefits for reservoir management.

Other biomanipulation techniques include

Continuation of river abstraction during the winter period to provide adequate food sources to “over-winter” the population of grazing zooplankton. In simple terms, zooplankton populations will consume any developing algae, the larger animals having a greater surface area of filtering combs which exert a greater grazing pressure on the developing algal populations.

However, the zooplankton are also grazed by any resident fish populations, hence another manipulation that could be applied is to reduce the number of certain fish species.

If the fish species that predate on zooplankton are removed, then the potential to reduce algae by zooplankton grazing will be increased (Renton et al., 1995).

In recent years, there has also been speculation of the effects of introducing top predator fish to eat the fish that predate on the zooplankton.

All these techniques contribute to the ongoing debate on how best to control the development of algal populations within storage reservoirs.

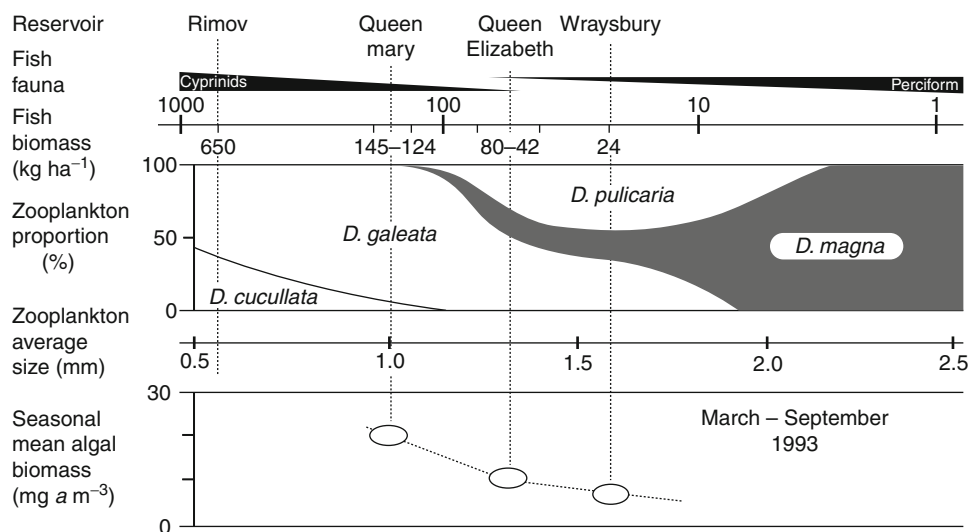
Figure 7 below illustrates the quantification of top-down effects in the trophic cascade hypothesis in three deep mixed Thames Valley reservoirs, data from the Czech Rimov reservoir is included.

Other speculative methods of algal control have involved the introduction of algal parasites; Chytrids have also been considered but are impractical at present.

The introduction of chemicals to kill algae has been previously mentioned.

Historically, copper sulfate used to be dosed in London's reservoirs but with mixed success. The main problems are associated with dosing the chemical and the subsequent impact on non-target species. Dead and decaying algae can introduce taste and odor problems to the water supply process, and floating, decomposing Cyanobacteria scums can be unpleasant to water body users and people living nearby. Dosing copper sulfate into acidic waters with little alkalinity may result in water quality problems in terms of regulatory failures. Copper salts may exacerbate later algal growth by killing zooplankton.

Chlorine has been used in some parts of the world. One of the main problems with the use of chlorine is that it tends to kill most of the zooplankton as well as the algae and the formation of undesirable by-products such as trihalomethanes (THMs). There are strict regulatory controls



Thames Water: Development of London's Potable Water Supply and the Role of Bankside Storage Reservoirs, Figure 7
Top-down effects in the trophic cascade hypothesis, from Steel and Duncan (1999).

on THMs and other by-products in most countries (WHO, EC, USEPA, etc.).

Where the water is eutrophic, it may be possible to reduce the available phosphorus concentration. In some locations within the UK, (not Thames Water) this has been applied with mixed success and is likely to succeed only in the short term. Generally, attempts at controlling phosphorus loadings have been by dosing with iron (III) salts. In alkaline water, considerable quantities of these salts are required to precipitate the phosphorus compounds. In acidic waters, the *pH* may exclude the use of iron salts. It is usually more economic to install mixing devices although in some basins, this may be impractical (shallow reservoirs with gently sloping sides), and the use of iron salts may be a consideration.

Maximizing the retention time in reservoirs is important in reducing the density of pathogenic microorganisms.

In the Thames Valley reservoirs, provided an appropriate retention time is achieved, a reduction of more than 99% of the fecal indicator species *Escherichia coli* has been recorded.

Recent desktop studies into the use of alternative techniques to control and monitor algae in deep storage reservoirs have included:

1. Alternative mixing devices
2. Artificial shading using floating reed beds
3. The application of barley straw
4. Ultrasound treatment
5. In-reservoir filtration
6. Floating pods with instrumentation recording real time data for early warning of algal bloom periods

Whatever techniques are used to control algal growth within the reservoir management complex, the inherited bankside storage reservoirs will remain an integral part of the source to tap treatment process philosophy adopted by Thames Water, UK.

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Cross-references

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THERMAL BAR

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Synonyms

Frontal zone

Definition

Cold zone – A cold-water lake area beyond the thermal bar involved in a three-dimensional convection.

Thermal bar – A frontal interface characterized by a strong mixing of waters at and near the temperature of maximal density in large deep temperate lakes during spring warming.

Warm zone – A stably stratified shallow warm-water lake area between a shore and the thermal bar.

Introduction

The thermal bar (hereinafter TB) is one of the most intriguing phenomena in physical limnology. In late spring, when lake warming starts, the total heat flux on the water surface varies in horizontal slightly. As a result, shallow near-shore areas are heated faster than deeper parts of a lake. As we know, the maximal freshwater density (T_{MD}) corresponds to the water temperature $T_{MD} = 3.98^{\circ}\text{C}$, with the parabolic density decrease on both sides from T_m that leads to the development of stable stratification in shallow areas (a warm zone) and a hydrostatically unstable situation in deep parts

of a lake (a cold zone). In the vicinity of the isotherm $T = T_{MD}$, one may expect formation of the double-cell convection with a strong descending current between the cells, which acts as a barrier and inhibits transport of waters from one zone to another and their mixing. Thus, most of dissolved substances including pollutants that come with waters of inflows are trapped in the warm zone. This relatively narrow area can be considered as a frontal interface and is called the thermal bar. As warming proceeds, TB propagates offshore until the deep-water temperature reaches 4°C . In such large and deep lakes like the Great Lakes in North America and Europe, the TB existence may last about 1 month. Hypothetically, the same phenomenon may occur in autumn due to preferential cooling of shallow near-shore regions. The effect of the autumnal TB is likely much lesser because of strong wind-induced dynamics and smaller temperature gradients typical for this season.

The discovery of TB belongs to the Swiss scientist François-Alphonse Forel, founder of limnology, who had qualitatively described its physical nature observing behavior of water temperature in Lac Lemman and termed the phenomenon “barre thermique” (thermal bar) (Forel, 1880). It took more than 50 years before the first detailed observational data became available. The Russian (Soviet) scientist Aleksei Tikhomirov has initiated the study of the thermal regime of Lake Ladoga – the largest European lake – including thorough research of TB; first in its northern Yakimvsky Bay (Tikhomirov, 1959) and then in the lake itself (Tikhomirov, 1963, 1968, 1982). Having used the basic ideas on formation of oceanic fronts, he had proposed a qualitative description of the double-cell circulation (Figure 1). His hypothesis was supported by observations of foam, oil, and small floating objects forming a band at the surface of thermal bar zone. The next detailed field TB studies have been performed by G.K. Rodgers (1965, 1966, 1968, 1971) in Lake Ontario. His findings confirmed the main results of Tikhomirov’s research. Based on heat content change estimates, both Tikhomirov and Rodgers suggested existence of heat advection directed from the warm zone toward TB. Rodgers also

suggested that a circulation pattern formulated by Tikhomirov is secondary compared to geostrophic currents in the warm zone, which are at least ten times stronger.

The thermal bar phenomenology

As it comes from the scaling analysis, the main parameters governing the TB propagation rate (TBPR) are the total heat flux on the water surface Q_s , bottom inclination, and the initial water temperature (heat content) of a lake T_0 . Indeed, in spring within a wedge-shaped basin with bottom inclination tangent μ the temperature change $(T - T_0)$ of a single water column with depth D in certain time t depends on the heat flux applied to a water column. Assuming for simplicity that Q_s and μ are constant in time and space, respectively, and heat advection is negligible, one can write, in a very simplified form,

$$\frac{T - T_0}{t} = \frac{Q}{D} = \frac{Q}{l\mu} \quad (1)$$

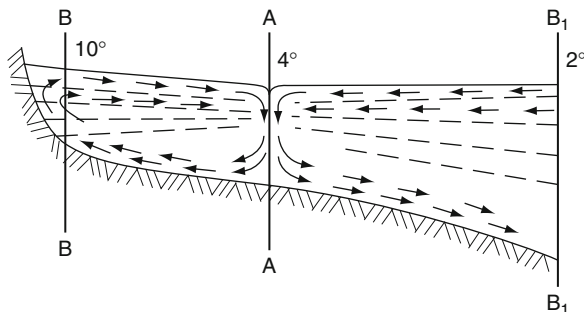
where $Q = Q_s/(\rho c_p)$ is the kinematic heat flux; ρ water density; c_p specific heat of water at constant pressure; and l is a horizontal distance from a shore to the isotherm $T(l) = T$. Substituting $T = T_{MD}$, the propagation rate l/t can be defined from (1) as follows:

$$\frac{l}{t} = \frac{Q}{(T_{MD} - T_0)\mu} \quad (2)$$

Thus, the higher Q and T_0 and the smaller μ , the faster TB propagates. The expression (2) was formulated by Elliott and Elliot (1970) in their laboratory study of the TB behavior in the wedge-shaped laboratory tank. According to their estimates based on results of experiments, TBPR was about $3 \cdot 10^{-4} \text{ m} \cdot \text{s}^{-1}$. In natural conditions TBPR may vary, depending on the bottom inclination and atmospheric forcing, e.g., $1.7 - 2 \cdot 10^{-2} \text{ m} \cdot \text{s}^{-1}$ in Lake Ladoga (Malm et al., 1993) and $1.2 \cdot 10^{-2} \text{ m} \cdot \text{s}^{-1}$ in Lake Ontario (Rodgers, 1966).

Estimates of the heat content change along cross sections perpendicular to TB confirmed the presence of horizontal heat transport from the near-shore warm zone to the TB zone (Malm et al., 1993). It was shown that the heat content change, compared to the surface heat flux, was higher in the TB zone and lower in the warm zone adjacent to TB. The model accounting for the horizontal heat transfer (Zilitinkevich et al., 1992) was found to better predict the propagation rate compared to earlier models considering only the surface heat flux as a source of warming (e.g., Elliott and Elliott, 1970).

The density (pressure) gradients on both sides of TB, under a geostrophic balance, form the so-called thermal wind flows, resulting in a strong cyclonic circulation in the warm zone and a weak anticyclonic circulation in the cold zone (see Figure 2 in Holland and Kay, 2003, p. 155). These flows, converging at TB, should damp the cross-frontal exchange. Results of experiments with



Thermal Bar, Figure 1 Scheme of the density-driven circulation in the near-shore zone of a lake during the thermal bar existence. Lines BB, AA, and B_1B_1 mark the near-shore warm, TB, and cold zones, respectively. (Taken from Tikhomirov, 1968, p. 169.)

natural tracers have shown that little mixing occurs between inshore and offshore waters, thus TB can be considered as a barrier separating warm and cold zones (Menon et al., 1971; Hubbard and Spain, 1973; Spain et al., 1976). Later observations (Gbah and Murthy, 1998; Rao et al., 2004) revealed that horizontal diffusion across the TB zone is consistently smaller than that directed along the front. The cross-frontal exchange coefficients are several orders of magnitude smaller than typical coastal values in the absence of TB.

Summary

The thermal bar is the unique physical phenomenon that should be studied further to better understand its nature, e.g., a clear formulation of the mechanism governing heat transport from the warm zone toward TB. Sergei Zilitinkevich (unpublished manuscript) suggested that it may occur due to baroclinic instability of geostrophic currents in the warm zone. Besides the strong effect on lake hydrodynamics, TB is every bit important from the standpoint of the impact on lake ecosystems, e.g., strong mixing in the TB zone, which leads to the longer life of all substances – including nutrients and pollutants – coming with inflow waters, in the lake proper. This in its turn may affect the seasonal development of plankton and a number of pollution events. Strong mixing may also accelerate sinking rates of newly formed organic matter and detritus, and then the former should intensify microbial activity in the bottom layers.

The limited space does not allow to give a comprehensive state-of-the-art review on TB studies performed. To get a better insight into the problem, a curious reader can be referred to the paper by Holland and Kay (2003). The authors nicely compiled most of observational, theoretical, and modeling studies carried out for the last 50 years, and suggested the outlook for further research.

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Cross-references

[Great Lake Processes: Thermal Structure, Circulation and Turbulent Diffusion Processes](#)
[Ladoga Lake and Onego Lake \(Lakes Ladozhskoye and Onezhskoye\)](#)
[Riverine Thermal Bar](#)

THERMAL REGIME OF LAKES

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Introduction

Heat is transferred to or lost from lake water through atmospheric exchange and with in- and outflowing rivers. There is also heat exchange with the bottom sediments. Since the depth varies over the lake, the heat exchange per unit mass is different in different water columns, which sets the water masses in an unstable condition

(baroclinic) and water movements are initiated striving to establish a stable condition (barotropic). The wind mixes the water so that the surface water is almost homothermal over the top meters. Further down, as a result of heating from the sun, when less and less solar radiation penetrates into deeper water, thermal stratification is established. Heating decreases the density of the upper layer. When the rate of atmospheric heat exchange with the water changes, convection within the water mass may be initiated and large water masses, maybe the entire lake water, will be part of the convective circulation.

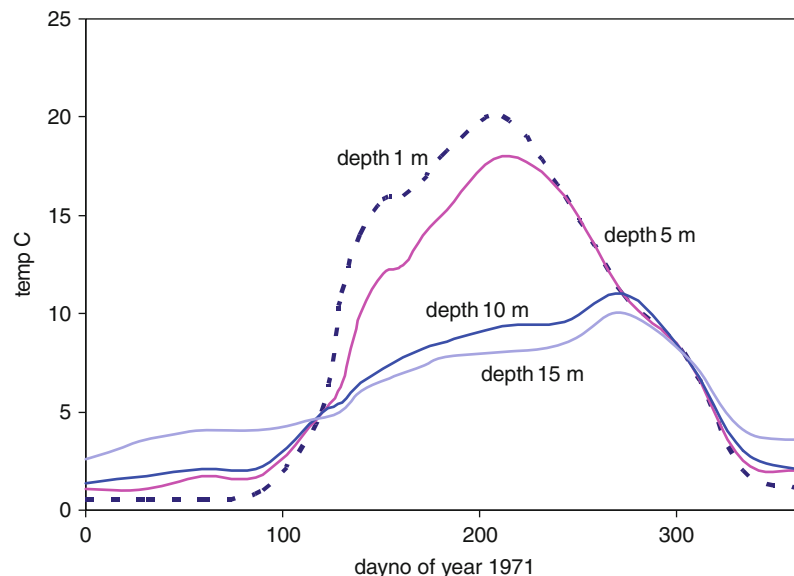
Thermal character of lakes

Fresh water has its greatest density at 4°C, which means that in regions of cold winters, the bottom water is warmer than the surface water. Most lakes of the world are in temperate zones, where the winter temperature falls below 4°C. If not very shallow, these lakes are stratified in the summer with warm water at a temperature close to the air temperature at top and much colder water at the bottom. In the winter they may be ice covered through the winter or for short periods with water at or near 0°C at the surface and bottom temperature near 4°C at the bottom. The lake water turns over and mixes completely, all the water being 4°C, in the spring and in the autumn. These lakes are called temperate lakes or dimictic lakes. In a warm climate the lake water temperature never drops below 4°C. In these tropical or monomictic lakes vertical mixing to considerable depth or over the full depth occurs in the winter, when the surface temperature decreases to that of the bottom temperature. Lakes in the Arctic behave much as the temperate lakes, but in some of them the water temperature never reaches 4°C. Lakes that have year-round ice and never mix are called amictic lakes.

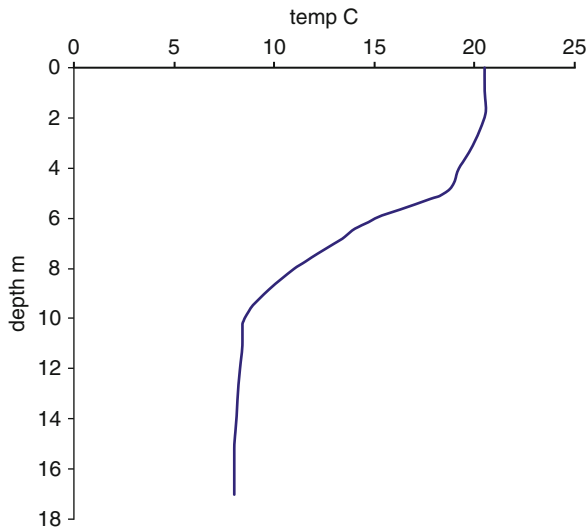
Development of vertical stratification

The dynamics of the temperature development in a temperate lake is described below starting from the homothermal situation in late autumn when the entire lake water is at the maximum density 4°C, which is the end of the autumn turnover period. From then on the water surface is cooled down mainly from longwave back radiation. When the weather is calm and the lake small, the surface temperature may drop to 0°C and ice may be formed already when most of the water is at 4°C. When there are strong winds acting on the lake a temperature profile with increasing water temperature from 0°C at the surface to 4°C or colder at the bottom develops before the lake freezes over. In not-so-deep wind-exposed lakes, the water temperature near the bottom may be very low and close to the surface temperature. It may also be that the lake only freezes over for short periods or not at all, and that the water temperature at the surface is some degrees above freezing point.

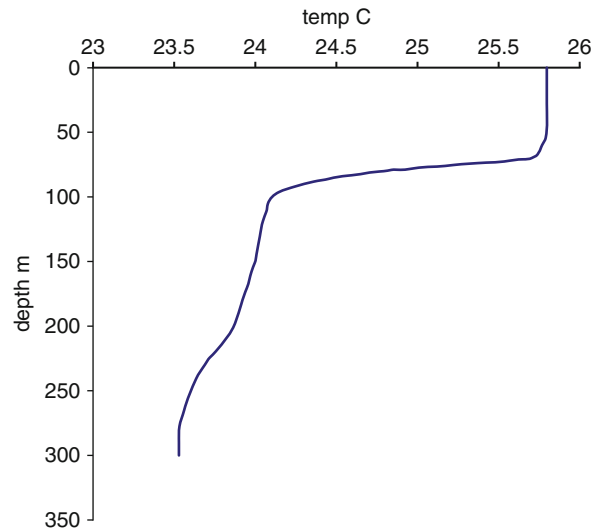
When there is a stable ice cover, there is no exchange with the atmosphere; the lake is almost insulated from the atmosphere. Instead, some heat is gained from the sediments, and the lake water becomes warmer throughout the winter. The temperature variation over the year of Lake Velen, Sweden, is shown in [Figure 1](#). When the ice disappears in spring, the whole lake water becomes homothermal at 4°C rather fast, because of rather intense solar radiation. The whole water mass mixes. This is the beginning of the spring turnover period. In the course of spring, the water is heated further and remains through wind mixing homothermal to considerable depth until the water is 6–10°C, although most of the solar radiation is absorbed near the surface. Thereafter the temporary gradients are too large for the wind to mix the water to



Thermal Regime of Lakes, Thermal Regime of Lakes, Figure 1 Temperature variation at different depth in Lake Velen, Sweden.



Thermal Regime of Lakes, Thermal Regime of Lakes,
Figure 2 July stratification in Lake Velen, 1971. Water depth 17 m. Processed from data in Falkenmark (1973).



Thermal Regime of Lakes, Thermal Regime of Lakes,
Figure 3 August temperature profile in Lake Tanganyika 1997. Processed from data in Huttula (1997). The lake has three basins, the deepest being 1,472 m. The sill levels between the basins are at 655–700 m depth.

considerable depth. The wind mixes the surface water only to some depth, so at lower depth the temperature gradient becomes quite sharp. A thermocline develops separating warm epilimnion water and cold hypolimnion water. The sharp temperature gradients reduce the vertical mixing between epilimnion and hypolimnion, which means that the gradient increases and becomes even sharper, which means that the thermocline becomes rather stable even when the winds are strong. An example of summer stratification is shown in Figure 2. The depth of the thermocline usually increases over the summer and the gradient becomes sharper.

In autumn the surface water is cooled down until the temperature difference between the epilimnion and hypolimnion is small and the thermocline can be broken by strong winds. There is mixing between surface and bottom water. The water is homothermal in this autumn turnover period. The entire lake continues to cool down and remain homothermal until the water temperature is 4°C. From then on the water at the surface cools down faster than the bottom water.

As already mentioned, in a tropical lake the surface water is always warmer or at the same temperature as the bottom water. A summer temperature profile is shown in Figure 3.

Horizontal gradients

Lakes which are not very large are horizontally rather well mixed. However, during days of intense solar radiation the water in shallow bays becomes warmer than the water far away from the shores. The temperature difference is minor, maybe 1°C, because convective currents striving to eliminate the temperature difference are induced. In

large lakes such as the North American Large Lakes or the Russian lakes Ladoga and Onega, a thermal barrier may develop, when near-shore surface water is heated to more than 4°C while the water far out in the lake is still below 4°C. Somewhere in between the water is at a maximum density at 4°C. Convection cells are initiated. Water is moving at the surface outward from the shore, mixes with colder water, becomes 4°C, and sinks toward the bottom due to its high density. Cold water from the main part of the lake moves inward, becomes colder, and when it is 4°C it sinks. The two convective cells meet where the temperature is at maximum density. No water passes this thermal barrier. This means that pollutants can be trapped at the shoreside of the thermal bar. The thermal bar moves outward in spring and early summer. In Lake Ladoga, it usually exists for more than a month. Temperature differences of more than 20°C have been observed.

If a lake consists of several basins, separated by sills, the bottom water is likely to have different temperatures except during the turnover periods.

Heat budget

The surface water temperature of a lake is close to that of the air, but the heat balance of a lake is determined by many processes. The heat budget is:

$$\frac{\Delta \text{HEAT}}{\Delta t} = \rho c_p \int A(z) T(z) dz$$

$$= A_0 (R + H_{\text{sens}} - H_{\text{lat}} + H_{\text{sed}}) + \rho c_p \Delta T Q$$

The first term is change of heat content over time, which is determined from the second term with ρ as density of water, c_p as the heat capacity, $A(z)$ is the lake area at depth z , and T is the corresponding temperature. On the right-hand side, A_0 is the lake surface area, ΔT is the temperature difference between inflowing river water and outflow with Q as the river inflow assumed to correspond to the outflow. H_{sens} is sensible heat flux into the lake, which is a function of the temperature difference between the atmosphere and the surface water. H_{lat} is the lateral heat loss from evaporation. The heat flux from the sediments, H_{sed} (or to the sediments in the summer), is significant only in ice covered lakes, where all the other fluxes are small. The net radiation R , is the dominating term and consists of four large fluxes:

$$R = R_{\text{sol}}(1 - \text{albedo}) + R_{\text{long}} - R_{\text{back}}$$

R_{sol} is the shortwave solar radiation, of which albedo time R_{sol} is reflected back to the atmosphere. The albedo is less than 10%; thus most of the solar radiation penetrates into the water. The longwave radiation, R_{long} , from the atmosphere can be estimated from the Stefan law. The emissivity depends on the cloudiness and the humidity of the atmosphere. On a clear day it may be 0.8 and on a rainy day close to unity. The back radiation, R_{back} , from the water surface is longwave radiation from the water and can be determined from the Stefan law with emissivity close to unity (0.97).

The shortwave radiation penetrates into the water and is absorbed at decreased rate as it penetrates to greater depth. In a low transparent lake, as most eutrophic lakes, all the shortwave radiation is absorbed not far from the surface. The penetration of the solar radiation can be determined, when the extinction coefficient, λ , of the water is known:

$$R(z) = R_{\text{sol}}(1 - \text{albedo}) e^{-\lambda z}$$

A warm summer day in southern Sweden with solar radiation of 600 W/m^2 during daytime when the air temperature is 25°C and the water temperature is 20°C , the sensible heat flux is about 50 W/m^2 , the latent heat loss 40 W/m^2 , the incoming longwave radiation about 370 W/m^2 , and the back radiation 420 W/m^2 resulting in a net flux into the lake of 560 W/m^2 , which in a 12-h period would heat a homothermal 5 m deep lake by about 1°C . During night there is no solar radiation, and since the air temperature usually is less than the water temperature, the sensible heat flux is a loss of heat. The net heat flux, if the night temperature is 17°C , is a loss of heat of about 120 W/m^2 , which would mean a reduction of the water temperature of about 0.2°C during the night.

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Cross-references

- [Circulation Processes in Lakes](#)
[Climate Change: Factors Causing Variation or Change in the Climate](#)
[Hydrodynamics of Very Shallow Lakes](#)
[Ice Covered Lakes](#)
[Lake Ice](#)
[Mixing in Lakes](#)
[Stratification in Lakes](#)
[Thermal Bar](#)

THERMOBARIC STRATIFICATION OF VERY DEEP LAKES

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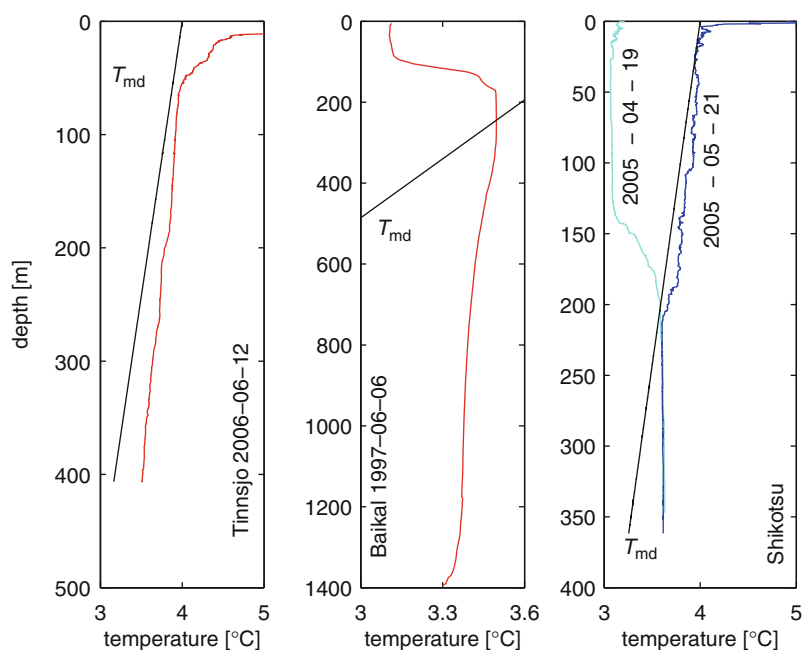
Definition

Thermobaric stratification refers to stable density stratification of natural water bodies, which results from the temperature dependence of the compressibility of water.

This feature can be observed in lakes of very low concentrations of dissolved substances. These lakes must be deep enough and situated in the appropriate climate zone.

Introduction

Although the compressibility of water is small, it permits a noticeable increase of in situ density under pressure, e.g., at great depth in lakes. Compressibility slightly decreases over the range of limnologically interesting temperatures. As a consequence, the temperature of maximum density T_{md} of pure water is shifted from 4°C to lower temperatures, by about 0.2 K at 100 m depth.



Thermobaric Stratification of Very Deep Lakes, Figure 1 Temperature profiles of thermobarically stratified lakes: *left panel* Tinnisjø, Norway, during (early) summer stratification above temperature of maximum density, T_{md} ; *central panel* Lake Baikal, Siberia, Russia, during (late) winter stratification with vertical transition through T_{md} ; *right panel* Lake Shikotsu, Hokkaido, Japan (From Boehrer and Schultze, 2008. With permission of American Geophysical Union).

Very deep freshwater lakes hence can have temperatures significantly smaller than 4°C (e.g., Yoshimura, 1936; Boehrer et al., 2008).

The T_{md} profile can be included in a depiction of measured temperatures against depth (see Figure 1). At any depth, moving away from T_{md} indicates decreasing density. In conclusion, left of the T_{md} profile falling temperatures toward shallower depths indicates stable stratification, while right of the T_{md} profile, the opposite is true. At the intersection with the T_{md} profile, a temperature profile must be constant for stability reasons. Hence, this is the maximum temperature in the profile of an ideal pure water lake (see Figure 1 central). Above and below the intersection, the temperature profile is stable on all depths.

As a consequence, such lakes can go from summer stratification into winter stratification without experiencing a full overturn. However, the small density gradients guarantee large-scale mixing within the water body. As a consequence, deep waters of thermobarically stratified lakes usually are well supplied with oxygen. During the transition into summer stratification, the temperature profile is kept close to the T_{md} profile over a wide depth range (Figure 1, right) with a nearly isothermal water body below, if horizontal differences are continuously negligible. In larger lakes, these features appear less clearly, and the deeper temperature profile is locked between T_{md} profile and a vertical line (Figure 1, left). In Lake Baikal,

the density stratification does not break at any time during the annual cycle. The stable density gradient is sustained by partial deep water renewal (Weiss et al., 1991; Wüest et al., 2005), i.e., by advection of cold water parcels from areas close to the side walls into the deep abyss.

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Cross-references

[Baikal, Lake](#)
[Stratification in Lakes](#)
[Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology](#)

THREE GORGES PROJECT ON THE YANGTZE RIVER IN CHINA

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Acronyms

a.m.s.l.—Above Mean Sea Level

CTGPC—China Three Gorges Project Corporation

RCC—Roller Compacted Concrete

TGHP—Three Gorges Hydropower Plant

TGP—Three Gorges Project

Introduction

China Yangtze Three Gorges Project (TGP), as one of the biggest hydropower-complex projects in the world, serves as the key project for improvement and development of Yangtze River. The name “Three Gorges” is based on three historically famous gorges, namely, Qutangxia, Wuxia, and Xilingxia, occupying about 200 km of Yangtze River. The dam is located in the areas of Xilingxia gorge, lowest one of the three gorges of the river, which controls a drainage area of 1 million square kilometers, with an average annual runoff of 451 billion cubic meters. The open valley at the dam site, with hard and complete granite as the bedrock, has provided the favorable

topographical and geological conditions for the construction of the dam. The first modern river development plan for the three gorges was drafted by Dr. Sun Yat-Sen in 1919 in his book *The international development of China* (Sun, 1919). The idea of constructing a huge dam was perhaps inspired by the successful story of the US Hoover Dam during the 1930s, and the official investigating and planning work was not even interrupted by the anti-Japanese war (1937–1945) and the following civil war. In 1992, The National People's Congress approved the dam with the result: out of 2,633 delegates, 1,767 voted in favor, 177 voted against, 664 forfeited, and 25 members did not vote. On December 14, 1994, the construction of the Three Gorges project was officially started with a three-phase project period ending at the year 2009. The dam body is located at Sandouping (coordinates: E111°0'36', N30° 9'48'), about 10 km northwest of Yichang city. A scenery photo of Qutangxia is shown in [Figure 1](#), and the general sketch of the dam location, the Yangtze River Basin together with China overview map is displayed in [Figure 2](#).

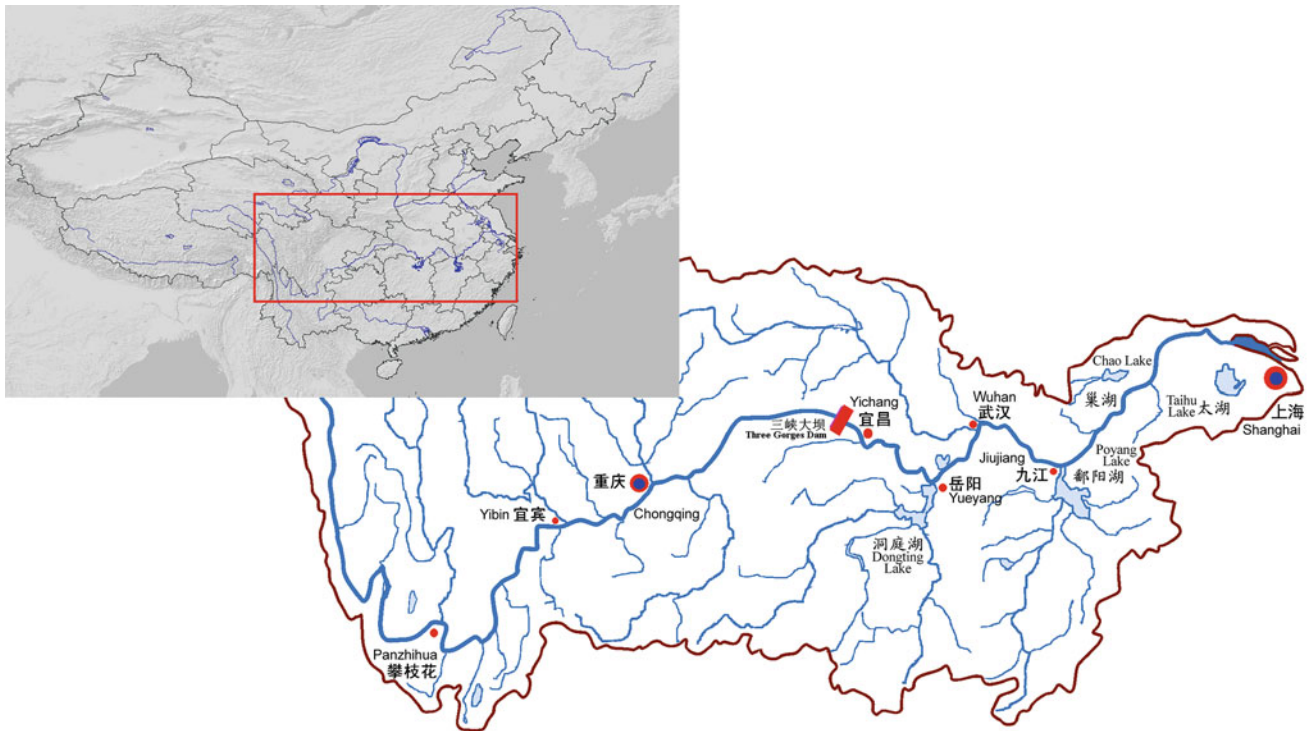
Some important features of the TGP project are described below, with the information source mainly from CTGPC (2011).

Flood control

The Three Gorges Reservoir is not the largest in terms of capacity in the world, and its reserved flood storage is calculated to be able to cut flood peak of 27,000–33,000 m³/s with a maximum peak of 116,110 m³/s. The standard water level of the dam is designed to be 175 m a.m.s.l. A bird's eye view of the dam can be seen in [Figure 3](#).



Three Gorges Project on the Yangtze River in China, Figure1 A view of three gorges (photo: Lars Bengtsson).



Three Gorges Project on the Yangtze River in China, Figure 2 Sketch of Yangtze River Basin and three gorges dam.



Three Gorges Project on the Yangtze River in China, Figure 3 Three gorges dam.

The flood control standard of the middle and lower reaches of the Yangtze, especially the Jingjiang Section, is to be upgraded from the previous level of preventing under-10-year floods to the current level of preventing 100-year floods. Some 15 million people and 1.5 million hectares of farmland in the Jiangnan Plain are protected from flood threats, and devastating plagues of massive death tolls caused by big floods can be averted. For comparison, some historical flood records of Yangtze River are listed in Table 1.

Power generation

The Three Gorges Hydropower Plant (TGHP) contains 26 turbine-generator units, each with an installed capacity of

700 MW. Additional six 700 MW units in the Right Bank Underground Powerhouse are under construction. Its total installed capacity amounts to 22,500 MW, and its expected annual average power generation accounts up to 84.7 TWH, so the TGHP ranks the biggest in the world with remarkable power generation benefit. At present, TGHP electricity is transmitted uninterruptedly to Central China, East China, Guangdong, and Chongqing with the maximum transmission range of 1,000 km (Table 2).

Navigation

Backwater of the TGP reservoir goes as far as to the southwest metropolitan area of Chongqing; therefore, it improves greatly the 660 km long waterway, which

Three Gorges Project on the Yangtze River in China, Table 1 Flood records of Yangtze River (1931, 1935, 1949, 1954, and 1998)

1931	The flood in 1931 struck an area of 130,000 km ² with 3.4 million hectares farmland and 1.8 million houses inundated, 28.6 million people affected, and 145,000 people killed, causing an approximate economic loss of 1.345 billion YinYuan (Silver Coin)
1935	The flood in 1935 hit an area of 89,000 km ² in the middle and lower reaches of the Yangtze River, affecting six provinces, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang and ten million people, 1.5 million hectares of farmland inundated, and 142,000 people killed, causing an approximate economic loss of 0.355 billion YinYuan (Silver Coin)
1949	The flood in 1949 inundated 1.8 million hectares farmland, affected 8.1 million people, and caused the death of 5,699 people in the middle and lower reaches of the Yangtze River
1954	The damages caused by the flood in 1954 in the middle and lower reaches: 3.2 million hectares farmland and 4.27 million houses inundated, 18.9 million people and 123 counties and cities affected, 33,169 people killed, and the interruption of the Beijing-Guangzhou Railway for 100 days
1998	The flood in 1998 struck a large area of the Yangtze Valley. The country went all out to fight against the flood for nearly 3 months with large quantities of people and materials employed. More than RMB 13 billion worth of flood-fighting materials were dispatched from all around the country, and about 6.7 million people and hundred thousands of soldiers took part in the fighting. However, the flood still caused great losses with 239,000 ha farmland inundated, 2.316 million people affected and 1,526 people killed in the four provinces of Hunan, Hubei, Jiangxi, and Anhui

Three Gorges Project on the Yangtze River in China, Table 2 Major parameters of the TGHP units compared with some larger power plants

Parameters	Three Gorges Project CHINA	Grand coulee USA	Itaipu Brazil/Paraguay	Guri Venezuela	Krasnoyarsk Russia
Turbine					
Maximum head (m)	113.0	108.2	126.7	146	100.5
Rated head (m)	80.6	86.9	112.9	130	93
Minimum head (m)	71.0(61.0)	67.0	82.9	111	76
Rated output (MW)	710	612/716	715	610	508
Maximum output (MW)	852	827	740/808	730	508(505)
Rated spinning speed (r/min)	75	85.7	90.9/92.3	112.5	93.8
Runner diameter (m)	9.525(9.800)	9.86/9.22	8.45	7.163	7.5
Generator					
Rated capacity (MW)	778	718	823.6/737.0	700	500
Maximum capacity (MW)	840	710/825.6	823.6/766	805	
Frequency (Hz)	50	60	50/60	60	50
Cooling	Water cooling of stator	Water cooling of stator	Water cooling of stator	Air cooling	Water cooling of stator
Rated voltage (KV)	20	15	18±5%	18	15.75
Insulation levels	F	B	F	B	
Thrust load (t)	4,050(4,100)	4,700	4,056 and 4,400	2,667	
Inner diameter of stator (m)	18,500(18,800)	18,790	16,000	13,650	16,100

enables 10,000-tonnage fleets to navigate between Shanghai and Chongqing. It is expected that the annual one-way shipment capacity of the Yangtze passing the dam will be upgraded from 10 to 50 million tons.

World-scale project construction

The construction of the main structure of the Three Gorges Water Conservancy Complex includes the following works: rock-and-earth excavation of 102.83 million cubic meters, concrete placement of 27.94 million cubic meters, rock-and-earth refill of 31.98 million cubic meters, metal frame installation of 256,500 t, and installation of twenty-six 700 MW turbine-generator units. Except the index of rock-and-earth refill, all the indices are the biggest among water conservancy projects which are already built or under construction.

Main infrastructure

Dam: The TGP dam is a concrete gravity one, made of 14.86 million cubic meters concrete, the biggest amount in the world. The maximum flood discharge capacity of the dam is 116,110 m³/s, which is the largest in the world.

Power plant: The TGHP is of dam toe powerhouse. The installed capacity of a single unit and annual power generation of the TGHP are both the largest in the world. The transmission lines of two ± 500 kV DC circuits and eleven 500 kV AC circuits are also among largest in the world.

Ship lock: The following indices are among the world records: total water head of 113 m, inland river ship lock of five stages, a lock chamber's effective dimension of 280 m $\times$ 34 m $\times$ 5 m, inland river ship lock with capacity to accommodate 10,000-tonnage fleets, maximum operating water head 49.5 m for a gate of its water exchange system, maximum water filling-emptying amount of 260,000 m³, and maximum side slope excavation of 170 m in height.

Shiplift: Single-way and one-step vertical shiplift with counterweight is employed in TGP complex, consisting of upstream and downstream approach channels, upper and lower lock heads and ship chamber section with a total length of 6,000 m. The ship lock will allow a maximum 3,000-tonnage ship passing through. The ship chamber has outline dimensions of 132 m $\times$ 23.4 m $\times$ 10 m and effective water area in it is 120 m $\times$ 18 m $\times$ 3.5 m. The maximum lifting height is 113 m and total lifting weight is about 11,800 t. The TGP's shiplift ranks the first in the world in terms of the major technical parameters.

Metal works: The TGP metal works include 386 gates of various kinds, 139 hoists of various kinds, 26 penstocks, all of which add up to about 256,500 t. The overall work quantity ranks the top among the world's hydraulic projects. The following indices are also the biggest in the world: the penstock's inner diameter of 12.4 m, the maximum height of ship lock miter gate of 38.25 m, and operating water head of 36.25 m, single gate's weight of 850 t.

Resettlement

According to a 1992 survey, the TGP reservoir impoundment will inundate 632 km² of land, including 24,500 ha of farmland and citrus land, and affect the households of up to 850,000 people. It was planned to relocate a population of 1.13 million. As of June 2008, a total of 1.24 million residents were relocated, which can be compared with Hubei Province's 60 million and Chongqing's 32 million inhabitants. Relocation was officially completed on July 22, 2008.

Technology features

River close-off and concrete cut-off wall construction

The river close-off and the concrete cut-off wall construction are two key issues in building Phase-II rock-and-earth cofferdam with following characteristics:

River close-off on the main channel: The TGP river close-off on the main channel features deep river, large inflow, intense construction, tight timetable, navigability during the close-off process, deep surface layer above the levee foundation, and other difficulties. The TGP dam is situated at the backwater region of the Gezhouba Reservoir, and during the close-off the maximum water depth at the riverbed was 60 m. It is crucial to prevent levee break and keep the levee stable during the bank-off advance. The solution was to adopt the program of pre-leveling, upstream single levee blocking, simultaneous bank-off advance from both banks, and downstream follow-up advance.

Deep water cofferdam and concrete cut-off wall: The TGP Phase-II cofferdam was built to guarantee the year-around construction in the foundation pit during the TGP Phase II construction period. The biggest difficulty of the Phase-II cofferdam is the construction of concrete cut-off wall.

River close-off on the diversion channel: The construction used steel-framed rock cages and alloy steel nets to roughen the bottom and to increase the friction of the riverbed, so that rock barrier was formed to reduce the difficulty of close-off and to ensure the stability of the fill materials. Two parallel levees were built to take the waterfall off the diversion channel, the upstream levee holding two third of the waterfall, the downstream one holding one third. On November 6, 2002, the TGP diversion channel was successfully closed off.

Fast concrete placement

Total concrete placement in the TGP construction amounts to 28 $\times$ 10⁶ m³. Advanced equipment and fast concrete placement technology were applied to ensure the quality. Concrete placement on the TGP dam started in 1998 and finished during 2001.

High slope

High Side Slope of Three Gorges Ship lock: The double-way and five-step ship lock was excavated through the ridge to the left of the hydropower complex, with

upstream and downstream approach channels connecting to the Yangtze main channel. The total length is 6,442 m including 1,607 m for main body section. Continuous high slopes lie on both sides of the ship lock, with maximum height of 170 m, and the area of more than 120 m high slope extends for about 460 m long.

Metal Structures of Ship lock: The total weight of metal structures and M&E equipment of the ship lock is over 40,000 t. The ship lock is equipped with automatic computer control. On June 10, 2003, the TGP reservoir was impounded to elevation 135 m, and on June 16, 2003, trial navigation on the ship lock started. In 2004, some 34 million tons of cargo have passed the ship lock.

The generator units

The TGP generator units have the features of large quantity, big capacity, and big range of water head variability. The installed capacity of each TGP unit is 700 MW. Technology breakthroughs have been made in the following aspects during the installation: automatic welding on large stator assembly, lamination stacking of large stator in the field, welding and measurement of rotor roundness, and controlling roundness of rotor rim and plate. The installation of the units is among the top records. In 2003, a total of six 700 MW units were installed and put into operation.

Environmental protection

Clean energy

Compared to the coal-fired power stations with equivalent electricity generation, Three Gorges Power Plant will decrease emission of 100 million tons of CO₂, 2 million tons of SO₂, a remarkable amount of nitrogen oxide, wastewater as well as solid waste. It will bring a great benign influence in improvement of environment, especially preventing acid rain and greenhouse effect in East and Central China.

Conservation of natural scenery and cultural relics

Three Gorges reach stretches a river length of 192 km and is famous for its beautiful, natural landscapes and historical and cultural relics. Due to the rise of water level caused by the reservoir, some natural landscapes are submerged. However, since most mountains upon the banks are as high as 800–1,000 m, while the maximum water level of the reservoir is designed as 175 m, most of the natural landscapes are unchanged. On the other hand, 44 relics are influenced by the water level rise. Some of them, such as Baiheliang sculpture and epigraphs in Fuling, are among the first class on the national protection list of relics. Another five relics are among the provincial protection list. Some relics are preserved at its original location, or transferred or copied to new place, such as Baiheliang sculpture, Zhang Fei Temple, Shibaozhai and Qu Yuan Temple. The ancient tombs of the submerged area have been unearthed on the basis of survey.

Biodiversity

Forty-seven precious botanic species are identified as endangered and are among the national-level protection list. Most of them are found in the area higher than 300–1,200 m, which is believed not to be much influenced by the project. Twenty-six rare wild animals are among the first and second classes of national list of protected animals, most of them live in high mountain areas, and thus not influenced by the submerge. A number of national conservation zones are also set up to protect the wild animals and botanic species of this area.

Three Gorges dam has impacts on the migrating route and living locations of local fish species, especially *Chinese Sturgeon* (*Zhonghuaxun*, a large and rare fish species). This negative impact has been known when the Gezhouba dam was built in the 1980's. Some artificial breeding projects have been carried out with proven success and some hundred thousands of baby fishes are released into the river every year.

Water quality

The reservoir has a mixed influence on the water quality. The increased flow during the dry period should improve the water quality downstream and relieve the intrusion of saline tide in the delta area to East China Sea. On the other hand, the sewage discharged into the river is estimated to be over 1.35 billion tons/year, which is the most severe pollution source for the river. The great challenge is also that a reduced water flow rate is more vulnerable for pollution.

Earthquake and bank stability

Risks of induced earthquake has been discussed and debated for a long time, and extensive researches have been made on the issue involving rock mechanics, geological structure, and tectonic perspectives. Most of the TGP-related constructions are designed based on earthquake magnitude class VII. A 300–800 m deep-hole earth stress observation is carried out at dam and reservoir site, and the earthquake-intensive observation is made on some fractured zones around the dam. The results indicated that the geologic structure at the dam is stable. The possible maximum earthquake intensity is estimated to be below magnitude class VI. Bank stability issue is getting more attentions in line with water level approaching 175 m. It has been identified that more than 70 cases of landslide or debris flow have been reported since 1982 (Ye, 2005). The same report also estimated the number of high-risk, unstable places to be over 1,130 sites, an alarming increase that must not be neglected.

Sedimentation

The sediment ranks as a crucial issue for reservoir construction worldwide due to its impacts on the function and lifetime of reservoirs. A pre-study calculated the incoming sediment transport amounts to be 530 million

Three Gorges Project on the Yangtze River in China,
Table 3 Projected accumulation of sediments in Three Gorges reservoir (billion cubic meters)

Years	2012	2022	2032
Low-value scenario	1.75	3.57	5.34
High-value scenario	3.12	6.26	9.21

tons/year, which may influence both the navigation and the dam function.

Early sediment research on Three Gorges reservoir began already during 1960s and has a history of more than 30 years. The research is done based on prototype observation, and mathematic and physical modeling with reference to the construction of the as-built projects. One important measure to decrease the sediments is to restore the ecological balance of the upper-stream area by various methods to protect the environment and control the soil losses, and thus, decrease sediment inflow to Yangtze River and improve the water quality. In some recent studies (CRSRI, 2007; BOH-CWRC, 2007), it is estimated that the total amount of accumulated sediments for year 2012 will be between 1.75 and 3.12 billion cubic meters, and the details of their results are presented in Table 3.

Concluding remarks

In terms of technology and engineering advancement, and to some extent in economic development with its positive impacts, the Three Gorges Project is of great success. A much desired research would be on a thorough cost-benefit analysis, taking all environmental, ecological, and socioeconomic aspects into consideration in an integrated and holistic approach. Issues related to ecological and environmental degradation, water quality deterioration, biodiversity impacts, reservoir-induced disaster as well as human resettlement are still highly controversial (Probe International, 2011). These issues need to be carefully studied and addressed, not only by the government but also by the academic societies.

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TITICACA LAKE

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Description

Lake Titicaca is the highest situated of the world's large lakes. It is partly in Bolivia and partly in Peru. It is covering 8,110 km². It is situated just south of the equator at an altitude of more than 3,800 m. There are more than 30 islands in the lake which reaches a maximum depth of about 300 m. The catchment area of Lake Titicaca including the lake itself is 56,000 km². The shore is highly indented, and the lake is divided into two lake basins, the upstream deep L. Chuquito and the smaller and shallow L. Huinamarca. The two lake basins are connected by the Tiquina Strait, which is in places only about 1.5 km wide. The depth of the smaller Lake Huinamarca is about 35 m. The surface level of Lake Titicaca is a mean 3 m above the narrow outlet sill at the border town of Desaguadero. The lake overflows to the southeast, into the Desaguadero River, which degenerates into the saline Lake Poopó and during very wet conditions further into the Salinas forming the TDPS system (Titicaca–Desaguadero–Poopó–Salinas system). The total area of the TDPS basin is about 144,000 km².

Geologically, Lake Titicaca lies in the complex gratin-faulted Altiplano, the Andean structural equivalent of the Basin-Range Province of North America and the various “median mass” structures of the Alpo-Himalayan orogenic belts. The Eastern Cordilleran side consists of much-folded Paleozoic geosynclinal sediments that are faulted against Cretaceous and other Mesozoic formations. The Altiplano depression is largely filled with late Tertiary and Quaternary lake deposits, volcanic deposits, and later by extensive alluvial fans.

There are no major cities around Lake Titicaca but numerous small Indian settlements. There are also extensive traces of the Inca and the Tiwanaku civilization. There are terraces indicating how the farmland was used. There are also clear signs of older and higher lake levels.

There is a swampy zone of totora fringed around Lake Titicaca. Further away, there are mountains. Some peaks reach 6,000 m a.s.l. There are six sub-basins within the Titicaca basin. The biggest one is the Ramis River basin extending over 15,000 km². The mean discharge of the Ramis River is 70 m³/s. The total inflow to Lake Titicaca is about 200 m³/s. The year can be divided into a wet summer period (November–March) and a dry winter

period (April–October). Although there are very high mountain peaks, only little precipitation falls as snow. The air temperature is rather constant throughout the year, with mean monthly temperature at lake level varying between 6°C and 12°C, but with extreme, 15–25°C, diurnal variations. The lake surface remains rather constant throughout the year at 12–13°C.

The outflow from Lake Titicaca is minor, about 30 m³/s, for such a large lake. The water balance of the lake is much dominated by the lake evaporation, about 1,300 mm. The outflow with the Desaguadero River corresponds to about 50 mm. The precipitation on the lake is about 800 mm, while the 200 m³/s river inflow corresponds to about 550 mm relative to the lake surface area. There have been short periods in modern time and extended periods in historical time when there has been no outflow. The lake level has even dropped so much that Lake Titicaca has been divided into two separate lakes. This happened 1,100–1,500 A.D., when the climate was dry for a very long time. The drought was devastating for the Tiwanaku civilization. The threshold level between the two Lake Titicaca basins is 19 m below the spill-over level of Lake Titicaca. The lake basin Huinamarca even almost dried out about 3,500 B.P. Today, there is a dam at the outlet at the town Desaguadero.

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TRANSBOUNDARY WATERS: RIVERS, LAKES, AND GROUNDWATERS

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Description

Transboundary rivers and lakes play a significant part in the world's water resources. In the UNECE (United Nations Economic Commission for Europe) region, for example, in the 56 countries of the region, all but the three island states share water resources with one or more countries. Transboundary basins cover more than 40% of the European and Asian parts of UNECE and sometimes extend outside the region. They link populations of different countries, are a major source of income for millions of people, and create hydrological, social, and economic interdependencies between countries.

List of country codes

Afghanistan	AF	Latvia	LV
Albania	AL	Liechtenstein	LI
Andorra	AD	Lithuania	LT
Armenia	AM	Luxembourg	LU
Austria	AT	The former Yugoslavia	
Azerbaijan	AZ	Republic of Macedonia	MK
Belarus	BY	Malta	MT
Belgium	BE	Moldova	MD
Bosnia and Herzegovina	BA	Monaco	MC
Bulgaria	BG	Mongolia	MN
China	CN	Montenegro	ME
Croatia	HR	Netherlands	NL
Cyprus	CY	Norway	NO
Czech Republic	CZ	Poland	PL
Denmark	DK	Portugal	PT
Estonia	EE	Romania	RO
Finland	FI	Russian Federation	RU
France	FR	San Marino	SM
Georgia	GE	Serbia	RS
Germany	DE	Slovakia	SK
Greece	GR	Slovenia	SI
Hungary	HU	Spain	ES
Iceland	IS	Sweden	SE
Islamic Republic of Iran	IR	Switzerland	CH
Ireland	IE	Tajikistan	TJ
Italy	IT	Turkey	TR
Kazakhstan	KZ	Turkmenistan	TM
Korea (Democratic		Ukraine	UA
People's Republic of)	KP	United Kingdom	GB
Kyrgyzstan	KG	Uzbekistan	UZ

The interstate distribution of water presents a particular challenge to those countries with arid or semi-arid climates in Eastern Europe, Caucasus and Central Asia, and in Southeastern Europe. Problems inevitably arise and upstream–downstream conflicts sometimes exist regarding water sharing. Other examples of transboundary lakes and rivers include the rivers and

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 1 Transboundary waters in the basins of the sea of the Barents Sea, the White Sea, and the Kara Sea

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Oulanka	– ^a	White sea	FI, RU	–
Tuloma	21,140	Kola Fjord > Barents Sea	FI, RU	–
Jacobselv	400	Barents Sea	NO, RU	–
Paatsjoki	18,403	Barents Sea	FI, NO, RU	Lake Inari
Näätämö	2,962	Barents Sea	FI, NO, RU	–
Teno	16,386	Barents Sea	FI, NO	–
Yenisey	2,580,000	Kara Sea	MN, RU	–
– Selenga	447,000	Lake Baikal > Angara > Yenisey > Kara Sea	MN, RU	–
Ob	2,972,493	Kara Sea	CN, KZ, MN, RU	–
– Irtysh	1,643,000	Ob	CN, KZ, MN, RU	–
– Tobol	426,000	Irtysh	KZ, RU	–
– Ishim	176,000	Irtysh	KZ, RU	–

^a5,566 km² to Lake Paanajärvi and 18,800 km² to the White Sea

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 2 Transboundary waters in the basins of the sea of Okhotsk and the Sea of Japan

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Amur	1,855,000	Sea of Okhotsk	CN, MN, RU	–
– Argun	164,000	Amur	CN, RU	–
– Ussuri	193,000	Amur	CN, RU	Lake Khanka
Sujfun	18,300	Sea of Japan	CN, RU	–
Tumen	33,800	Sea of Japan	CN, KP, RU	–

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 3 Transboundary waters in the basins of the sea of the Aral Sea and other transboundary surface waters in Central Asia

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Amu Darya	–	Aral Sea	AF, KG, TJ, UZ, TM	Aral Sea
– Surkhan Darya	13,500	Amu Darya	TJ, UZ	–
– Kafirnigan	11,590	Amu Darya	TJ, UZ	–
– Pyanj	113,500	Amu Darya	AF, TJ	–
– Bartang	–	Pyanj	AF, TJ	–
– Pamir	–	Pyanj	AF, TJ	–
– Vaksh	39,100	Amu Darya	KG, TJ	–
Zeravshan	–	Desert sink	TJ, UZ	–
Syr Darya	–	Aral Sea	KG, KG, TJ, UZ	–
– Naryn	–	Syr Darya	KG, UZ	–
– Kara Darya	28,630	Syr Darya	KG, UZ	–
– Chirchik	14,240	Syr Darya	KZ, KG, UZ	–
– Chatkal	7,110	Chirchik	KG, UZ	–
Chu	62,500	Desert sink	KZ, KG	–
Talas	52,700	Desert sink	KZ, KG	–
Assa	–	Desert sink	KZ, KG	–
Ili	413,000	Lake Balqash	CN, KZ	Lake Balqash
Murgab	46,880	Desert sink	AF, TM	–
– Abikajsar	–	Murgab	AF, TM	–
Tejen	70,260	Desert sink	AF, IR, TM	–

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 4 Transboundary waters in the basins of the sea of the Barents Sea, the White Sea, and the Kara Sea

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Ural	231,000	Caspian Sea	KZ, RU	–
– Ilek	–	Ural	KZ, RU	–
Atrek	27,300	Caspian Sea	IR, TM	–
Astara Chay	242	Caspian Sea	AZ, IR	–
Kura	188,000	Kura	AM, AZ, GE, IR, TR	Lake Jandari, Lake Kartsakhi,
– Iori	5,255	Kura	AZ, GE	Araks Arpachay, Baraji reservoir,
– Alazani	11,455	Kura	AZ, GE	Araks Govsaghynyn reservoir
– Debet	4,100	Kura	AM, GE	
– Agstev	2,500	Kura	AM, GE	
– Potkshovi	1,840	Kura	GE, TR	
– Ktsia-Khrami	8,340	Kura	AM, GE	
– Araks	102,000	Kura	AM, AZ, IR, TR	
– Akhuryan	9,700	Araks	AM, TR	
– Arpa	2,630	Araks	AM, AZ	
– Vorotan (Bargushad)	5,650	Araks	AM, AZ	
– Voghji	1,175	Araks	AM, AZ	
– Kotur (Qotur)	–	Araks	IR, TR	
Samur	7,330	Caspian Sea	AZ, RU	–
Sulak	15,200	Caspian Sea	GE, RU	–
– Andis-Koisu	4,810	Sulak	GE, RU	–
Terek	43,200	Caspian Sea	GE, RU	–
Malyi Uzen	13,200	Kamysh-Samarsk lakes	KZ, RU	Lakes of Kamysh-Samarsk
Bolshoy Uzen	14,300	Kamysh-Samarsk lakes	KZ, RU	

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 5 Transboundary waters in the basins of the Black Sea

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Rezvaya	740	Black Sea	BG, TR	–
Danube	801,463	Black Sea	AL, AT, BA, BG, CH, CZ, DE, HU, HR, MD, ME, MK, IT, PL, RO, RS, SK, SI, UA	Lake Iron Gates I and II, Lake Neusiedl
– Lech	4,125	Danube	AT, DE	–
– Inn	26,130	Danube	AT, CH, DE, IT	–
– Morava	26,578	Danube	AT, CZ, PL, SK	–
– Raab/Raba	10,113	Danube	AU, HU	–
– Vah	19,661	Danube	PL, SK	–
– Ipel/Ipoly	5,151	Danube	HU, SK	–
– Drava and Mura	41,238	Danube	AT, HU, HR, IT, SI	–
– Tisza	157,186	Danube	HU, RO, RS, SK, UA	–
– Somes/Szamos	16,046	Tisza	HU, RO	–
– Mures/Maros	30,195	Tisza	AL, BA, HR, ME, RS, SI	–
– Sava	95,713	Danube	BG, ME, MK, RS	–
– Velika Morava	37,444	Danube	BG, RS	–
– Timok	4,630	Danube	RO, UA	–
– Siret	47,610	Danube	MD, RO, UA	–
– Prut	27,820	Danube	MD, RO, UA	Stanca–Costesti reservoir
Kahul	–	Lake Kahul	MD, UA	Lake Kahul
Yalpuh	–	Lake Yalpuh	MD, UA	Lake Yalpuh
Cogilnik	6,100	Black Sea	MD, UA	–
Dniester	72,100	Black Sea	UA, MD	–
– Yahorlyk	–	Dniester	UA, MD	–
– Kuchurhan	–	Dniester	UA, MD	–
Dnieper	504,000	Black Sea	BY, RU, UA	–
– Pripyat	114,300	Dnieper	BY, UA	–
Elancik	900	Black Sea	RU, UA	–
Mius	6,680	Black Sea	RU, UA	–
Don	422,000	Black Sea	RU, UA	–
– Siversky Donets	98,900	Don	RU, UA	–
Psou	421	Black Sea	RU, GE	–
Chorokhi/Coruh	22,100	Black Sea	GE, TR	–
– Machakheliskali	369	Chorokhi/Coruh	GE, TR	–

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 6 Transboundary waters in the basin of the Mediterranean Sea

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Ebro	85,800	Mediterranean Sea	AD, ES, FR	–
Rhone	98,00	Mediterranean Sea	CH, FR, IT	Lake Emosson, Lake Geneva
Roia	600	Mediterranean Sea	FR, IT	–
Po	74,000	Mediterranean Sea	AT, CH, FR, IT	Lake Maggiore, Lake Lugano
Isonzo	3,400	Mediterranean Sea	IT, SI	
Krka	2,500	Mediterranean Sea	BA, HR	
Neretva	8,100	Mediterranean Sea	BA, HR	
Drin	17,900	Mediterranean Sea	AL, GR, ME, MK, RS	Lake Ohrid, Lake Prespa, Lake Skadar
Vijose	6,519	Mediterranean Sea	AL, GR	
Vardar	23,750	Mediterranean Sea	GR, MK	Lake Dojran
Struma	18,079	Mediterranean Sea	BG, GR, MK, RS	
Nestos	5,613	Mediterranean Sea	BG, GR	
Maritza	52,600	Mediterranean Sea	BG, GR, TR	
– Arda	–	Maritza	BG, GR	
– Tundja	–	Maritza	BG, TR	

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 7 Transboundary waters in the basins of the North Sea and Eastern Atlantic

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Glama	42,441	North Sea	NO, SE	–
Klaralven	11,853 ^a	North Sea	NO, SE	–
Wiedau	1,341	North Sea	DE, DK	–
Elbe	148,268	North Sea	AT, CZ, DE, PL	–
Ems	17,879 ^b	North Sea	DE, NL	–
Rhine	197,100 ^c	North Sea	AT, BE, CH, DE, FR, IT, LI, LU, NL	Lake Constance
– Moselle	28,286	Rhine	BE, DE, FR, LU	–
– Saar	7,431	Moselle	FR, DE	–
– Vechte	2,400	Swarte water > Ketelmeer > Ijs-selmeer > North Sea	DE, NL	–
Meuse	34,548 ^d	North Sea	BE, FR, NL	–
Scheldt	36,416 ^e	North Sea	BE, FR, NL	–
Yser		North Sea	BE, FR	–
Bidasoa	500	Eastern Atlantic	ES, FR	–
Mino	17,080	Eastern Atlantic	ES, PT	Frieira reservoir
Lima	2,480	Eastern Atlantic	ES, PT	Alto Lindoso reservoir
Douro	97,600	Eastern Atlantic	ES, PT	Miranda reservoir
Tagus	80,600	Eastern Atlantic	ES, PT	Cedillo reservoir
Guadiana	66,800	Eastern Atlantic	ES, PT	–
Erne	4,800	Eastern Atlantic	GB, IE	–
Foyle	2,900	Eastern Atlantic	GB, IE	–
Bann	5,600	Eastern Atlantic	GB, IE	–
Castletown	400	Eastern Atlantic	GB, IE	–
Fane	200	Eastern Atlantic	GB, IE	–
Flurry	60	Eastern Atlantic	GB, IE	–

^aBasin area until Lake Värnern^bArea for the Ems River Basin district^cArea for the Rhine River Basin district^dArea for the Meuse River Basin district^eArea for the Scheldt River Basin district^fThe Yser is part of Scheldt River Basin district

lakes of the Middle East where the rivers Euphrates and Tigres feed Turkey, Iran, Iraq, and Syria. Agreement exists to share the Anatolla reservoirs in the headwaters of these rivers.

In the case of Israel, 60% of its water comes from the occupied areas, the three main sources of the country's supply coming from Lake Kinneret (Sea of Galilee) which is fed by the River Jordan, a coastal aquifer which extends

Transboundary Waters: Rivers, Lakes, and Groundwaters, Table 8 Transboundary waters in the basin of the Baltic Sea

Basin/sub-basin(s)	Total area (km ²)	Recipient	Riparian countries	Lakes in the basin
Torne	40,157	Baltic Sea	FI, NO, SE	
Kemijoki	51,127	Baltic Sea	FI, NO, SE	
Oulujoki	22,841	Baltic Sea	FI, RU	
Jänisjoki	3,861	Lake Ladoga	FI, RU	
Kiteenjoki-Tohmajoki	1,595	Lake Ladoga	FI, RU	
Hiitolanjoki	1,415	Lake Ladoga	FI, RU	
Vuoksi	68,501	Lake Ladoga	FI, RU	Lake Pyhäjärvi and Lake Saimaa
Juustilanjoki	296	Baltic Sea	FI, RU	Lake Nuijamaanjärvi
Rakkonlanjoki	215	Baltic Sea	FI, RU	
Urpanlanjoki	557	Baltic Sea	FI, RU	
Saimaa Canal including Soskuanjoki	174	Baltic Sea	FI, RU	
Tervajoki	204	Baltic Sea	FI, RU	
Vilajoki	344	Baltic Sea	FI, RU	
Kaltonjoki (Santajoki)	187	Baltic Sea	FI, RU	
Vaalimaanjoki	245	Baltic Sea	FI, RU	
Narva	53,200	Baltic Sea	EE, LV, RU	Narva reservoir and Lake Peipsi
Salaca	2,100	Baltic Sea	EE, LV	
Gauja/Koiva	8,900	Baltic Sea	EE, LV	
Daugava	58,700	Baltic Sea	BY, LT, LV, RU	Lake Drisvyaty/Drukshiai
Lielupe	17,600	Baltic Sea	LT, LV	
– Nemunelis	4,047	Lielupe	LT, LV	
– Musa	5,463	Lielupe	LT, LV	
Venta	14,292 ^a	Baltic Sea	LT, LV	
Barta	–	Baltic Sea	LT, LV	
Sventoji	–	Baltic Sea	LT, LV	
Neman	97,864	Baltic Sea	BY, LT, LV, PL, RU	Lake Galadus
Pregel	15,500	Baltic Sea	LT, RU, PL	
Prohladnaja	600	Baltic Sea	RU, PL	
Vistula	194,424	Baltic Sea	BY, PL, SK, UA	
– Bug	39,400	Vistula	BY, PL, UA	
– Dunajec	4726.7	Vistula	PL, SK	
– Poprad	2,077	Dunajec	PL, SK	
Oder	118,861	Baltic Sea	CZ, DE, PL	
– Neisse	–	Oder	CZ, DE, PL	
– Olse	–	Oder	CZ, PL	

^aFor the Venta River Basin district, which includes the basins of the Barta/Bartuva and Sventoji rivers

south to the Gaza Strip, an aquifer under the West Bank, and a pumped storage reservoir supply from the Lebanon's Litani River.

Another example is the 190 km long Shatt al-Arab waterway into which the Euphrates and Tigris empty at Al-Qurnah. It has been the subject of a longstanding frontier dispute between Iran and Iraq for some 400 years or more. An agreement exists whereby the thalweg of the waterway has been agreed.

The case of the transboundary rivers and lakes of the UNECE region has been the subject of a detailed study by the countries of the region. The study divided the whole region basically in two subregions: the Southeastern Europe (SEE) and Eastern Europe, Caucasus, and Central Asia (EECCA).

The UNECE assessment of transboundary rivers, lakes, and groundwaters is the first ever in-depth report produced on the subject in the UNECE region.

The report covers 140 transboundary waters and 30 transboundary lakes as well as 70 transboundary aquifers located in Southeastern Europe, Caucasus, and Central Asia. The inventory of the study, reproduced here, is contained in [Tables 1–8](#) where first-order basins are presented in *bold*.

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Cross-references

[Nile Basin, Lakes](#)

TROPIC LAKE CLASSIFICATION

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Introduction

The world's lakes were formed by various means, but many by movement of the earth's crust, or by glacial or volcanic action. Some may have a surface area of a few square kilometers to thousands of square kilometers (for example, the Caspian Sea). Many lakes are aged as much as 20 million years (Aral Sea, Baikal, Caspian, Prespa, etc.).

However interesting age and formation may be, placing lakes in a class system is probably best by considering lake quality. In this respect a trophic classification is generally preferred to lake water mixing and circulation capability or fish community.

Trophic concept

The richness in nutrients of the lake is the basis for addressing the classification as follows:

- (a) Oligotrophic
- (b) Eutrophic
- (c) Mesotrophic
- (d) Dystrophic

Oligotrophic lakes

The nutrient-poor lakes or oligotrophic contain very low growth productivity except some plankton and some large fish. The clarity of the lake is such that a Secchi disk may have a reading of 10 m. In oligotrophic lakes, therefore, there is little production of organic matter few suspended algae, the phytoplankton yielding low chlorophyll averaging about 1.7 mg per cubic meter and little organic bed sediment. On the other hand, consumption of oxygen is low, leaving abundant oxygen throughout the depth.

Oligotrophic lakes have clean water, no weed problems, but poor fishing, and seldom in good agriculture land.

Eutrophic lakes

Compared to oligotrophic lakes, eutrophic lakes are rich in nutrients with high productivity, producing large numbers of phytoplankton which, as algae, tend to cloud the lake water. Because of this the Secchi disk gives much lower readings compared with oligotrophic of the order of 2.5 m. Eutrophic lakes produce much zooplankton and small fish which feed on the zooplankton.

A characteristic of eutrophic lakes is the depletion of oxygen in lower depths usually below the thermocline (below, say, 5.5 m, Kevern et al. 1996).

Trophic Lake Classification, Table 1 Phosphorus and chlorophyll concentrations and Secchi disk depths characteristic of the trophic classification of lakes

Measured parameter		Oligotrophic	Mesotrophic	Eutrophic
Total phosphorus (mg/m ³)	Average	8	26.7	84.4
	Range	30.–18	10.9–95.6	16–386
Chlorophyll (mg/m ³)	Average	1.7	4.7	14.3
	Range	0.3–4.5	3–11	3–78
Secchi disk depth (m)	Average	9.9	4.2	2.45
	Range	5.4–28.3	1.5–8.1	0.8–7.0

Because of the large concentration of phytoplankton, eutrophic lakes have chlorophyll concentrations averaging 14 mg per cubic meters and phosphorus concentration averages of 80 mg per cubic meter.

These lakes are often shallow with weed beds but usually having large numbers of fish due to the available plankton and benthic organisms.

The transition stage between oligotrophic and eutrophic lakes is the mesotrophic lake. The growth of plankton is intermediate, and the range of values of phosphorus and chlorophyll and Secchi disks overlap. Average values for all three concepts is given in the Table 1 which is taken from Wetzel (1983), and it can be seen that there are no fixed values of phosphorus or chlorophyll concentrations nor of Secchi values.

Dystrophic lakes

A dystrophic lake develops from the accumulation of organic matter from outside the lake. A tree-lined catchment where leaves are able to drop into the lake brings subsequent humic acids. Dystrophic lakes have usually low pH values but has clear but colored water resulting from organic acids. Such lakes are normally poor in calcium and plankton production and in fish population.

It is clear that a trophic classification of lakes may have many exceptions and interpretations and, in some cases, is dependent on the use to which the lake is put.

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Cross-references

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[Classification of Lakes from Origin Processes](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Nutrient Balance, Light, and Primary Production](#)

TSUNAMI EFFECT ON A COASTAL LAKE IN INDIA

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Introduction

Kalpakkam (12°34'N Lat. and 80°11'E Long.), situated on the east coast of India about 80 km south of Chennai (Figure 1), is known for existence of nuclear facilities, such as Madras Atomic Power Station (MAPS) and Prototype Fast Breeder Reactor (PFBR). The entire site covers approximately 1,500 ha. It is bestowed with a number of natural water bodies in the form of backwaters and lakes. One of them is a tiny brackish water lake (Kokilamedu lake) situated on the isolated northeastern side of the campus. It covers an area of 0.75 sq km during monsoon period, and the spread shrinks to 0.5 sq km during summer. The average depth is about 1 m and has a maximum depth of 3 m. The lake provides a conducive environment for the waders as well as for other aquatic and terrestrial fauna that inhabit the rich flora in and around the lake. A 50-m width strip of sand bream, which is covered by *Casuarina* and *Pandanus*, forms the barrier between the lake and Bay of Bengal. Occasionally, seawater intrusion into the lake takes place during high tides. Apart from the avian guests who visit during winter, the endemic avian fauna of the lake is comprised of some important bird species like pelicans, painted storks, black headed ibis, etc., along with fishes and amphibians. This lake has attracted the attention of ecologists due to two important events that have taken place during the last decade. During May 1995, a massive fish kill was observed, and this was attributed to natural eutrophication coupled with anoxic condition and high temperature (Venugopalan et al., 1998). The other important event which has affected the lake ecology is the mega December 2004 tsunami, which completely inundated the lake with seawater and brought massive amount of sediment from the sea into the lake (Satpathy et al., 2007, 2008). An increase in seawater influx was noticed after the event of the tsunami, which narrowed the sand barrier and destroyed the vegetation between the lake and the sea. Sketchy data available prior to tsunami revealed that the lake characteristic was close to a freshwater one. In spite of the above two events, no systematic and comprehensive scientific investigation on the lake ecology was available till August 2006. Considering the ecological importance of the lake, a scientific investigation with respect to various

ecological parameters has been initiated since September 2006, with the following objectives:

- To create a baseline data on physicochemical parameters for future impact studies
- To assess the change that has taken place after tsunami by comparing the available pre-tsunami information.
- To suggest and implement appropriate measures to improve and restore the ecology of the lake

In the present entry only the first two objectives have been addressed.

Based on the climatology of this location, the whole year is divided into three seasons: (1) post-monsoon/summer (February–May), (2) pre-monsoon or south-west monsoon (June–September), and (3) northeast monsoon (October–January). The northeast monsoon is active in this area, and a bulk (70%) of rainfall occurs during this period. The average rainfall here is about 1,200 mm.

Methodology

Water samples were collected once in a week for a period of 1 year (September 2006–August 2007) from a fixed location in pre-cleaned polythene bottles and analyzed for various physicochemical and biological parameters. DO was estimated following standard methods (Grasshoff et al., 1983). pH measurements were carried out by a pH meter (CyberScan PCD 5500). Conductivity of the water samples were measured by a conductivity meter (CyberScan Con 100). The dissolved micronutrients such as, nitrite + nitrate, ammonia, silicate and phosphate, along with total nitrogen (TN), total phosphorus (TP) and chlorophyll-*a* were estimated by following standard methods (Parsons et al., 1984; Grasshoff et al., 1983). Statistical analyses such as correlation matrix and cluster analysis were carried out by using XLStat 2008 software. Similar work on water quality characteristics carried out during June 1994–May 1995 (unpublished) was used as pre-tsunami data to assess any change.

Results and discussion

The results obtained were pooled into monthly average values to get a clarity of the seasonal variation of the physicochemical parameters and chlorophyll-*a* and are reported here.

pH

The lake water was found to be alkaline throughout the year with pH > 8 in almost all the observations. It ranged from 7.6 to 8.9 with the monthly average value ranging from 8.00 ± 0.36 in February 2007 to 8.60 ± 0 in September 2006 (Figure 2a). Highest and lowest values of pH were observed during the period of high and low salinity (conductivity) regime of the lake waters. pH values between pre- and post-tsunami showed that the values have increased marginally during post-tsunami period (Figure 2b). Inundation of seawater, which is more alkaline



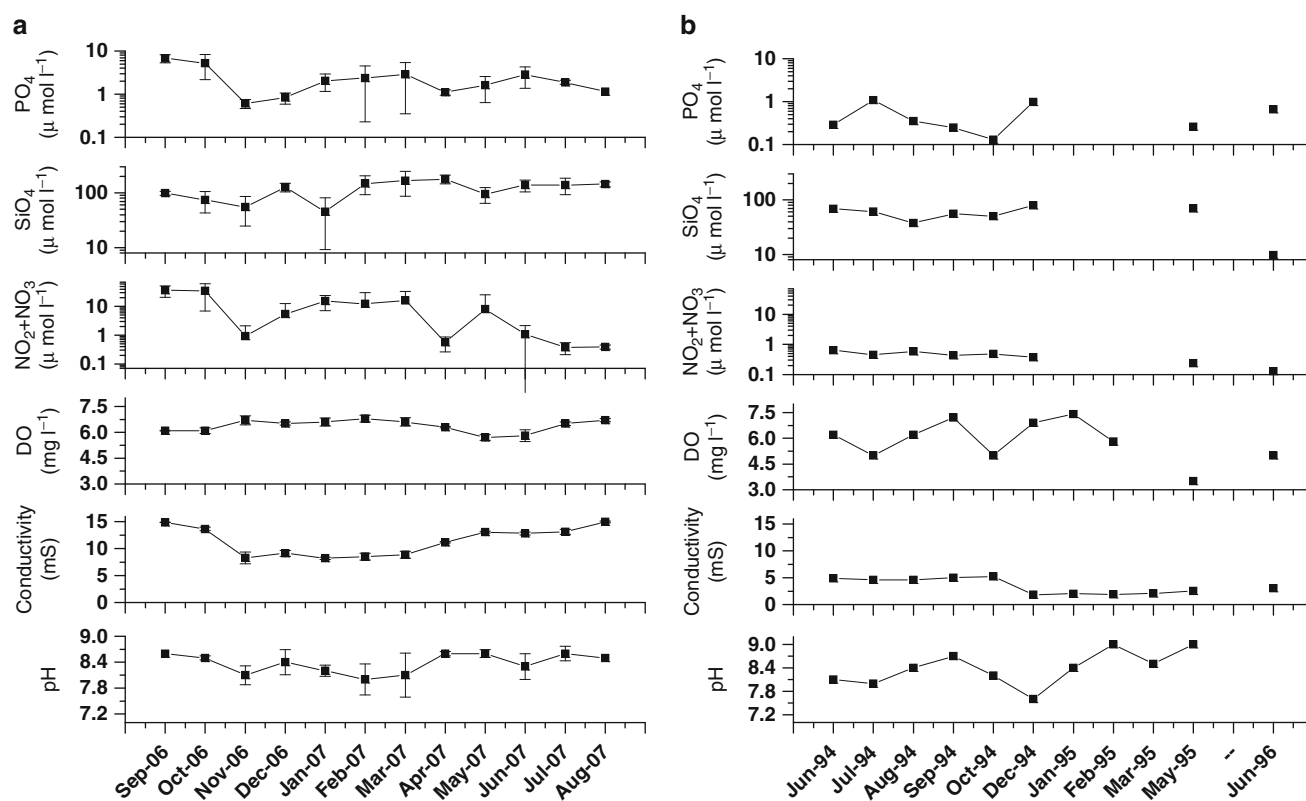
Tsunami Effect on a Coastal Lake in India, Figure 1 Kokilamedu lake showing sampling location.

in nature, into the lake during the tsunami has pushed the pH up. Moreover, there has also been sporadic incursion of seawater into the lake as the barrier between sea and the lake has been thinned down during the tsunami. Positive correlation ($p \geq 0.000$) obtained between pH and salinity (conductivity) (Table 1) corroborates the above observation and explanation.

Conductivity

The lake represented a typical brackish water character with conductivity ranging from 7.80–18.41 mS during the post-tsunami period. The monthly values varied between 9.90 ± 0.57 during January and 18.03 ± 0.54 during August (Figure 2a). Values of conductivity gradually decreased from September to January and then increased up to August. It showed a clear unimodal

oscillation with a peak during pre-NE monsoon and a fall during the monsoon period. During post-monsoon and summer the conductivity remained comparatively low due to the rain water received during the monsoon period. The extensive green foliage available near the lake coupled with location of the lake at low elevation possibly was responsible for reduced evaporation leading to observation of relatively low conductivity even during summer. Reduction in water level was noticed during the late summer and pre-monsoon leading to increase in conductivity. One of the interesting observations is that, the conductivity has increased significantly from 1.83 mS during May 1995 to 18.41 mS during August 2007. Seawater intrusion during the December 2004 tsunami and occasionally thereafter could be the reason for the above observation. However, typical



Tsunami Effect on a Coastal Lake in India, Figure 2 Seasonal variation in physicochemical parameters of Kokilamedu Lake during post-tsunami (September 2006–August 2007) (a) and pre-Tsunami (June 1994–May 1995) (b) periods.

Tsunami Effect on a Coastal Lake in India, Table 1 Correlation matrix (Pearson)

Variables	pH	Salinity (conductivity)	DO	$NO_2 + NO_3$	NH_3	TN	SiO_4	PO_4	TP	Chl- <i>a</i>
pH	1									
Salinity (conductivity)	0.688 ^a	1								
DO	−0.427 ^a	−0.648 ^a	1							
$NO_2 + NO_3$	0.063	0.141	−0.124	1						
NH_3	−0.167	0.077	−0.359 ^b	−0.133	1					
TN	0.043	0.422 ^a	−0.380 ^a	0.302 ^b	0.724 ^a	1				
SiO_4	0.204	0.121	0.044	−0.098	0.062	0.039	1			
PO_4	0.178	0.360 ^b	−0.264 ^c	0.739 ^a	0.214	0.599 ^a	0.011	1		
TP	0.203	0.335 ^b	−0.277 ^c	0.751 ^a	0.206	0.526 ^a	0.154	0.884 ^a	1	
Chl- <i>a</i>	0.367 ^b	0.337 ^b	−0.341 ^b	−0.098	0.059	−0.023	0.404 ^a	0.044	0.157	1

^a $p \geq 0.000$

^b $p \geq 0.005$

^c $p \geq 0.01$

coastal water conductivity (~ 55 mS) was never observed in spite of seawater intrusion. Conductivity values of the lake just after Tsunami, which might have been very close to typical seawater conductivity, has been reducing since then as a result of the precipitation received during post-tsunami period.

Dissolved oxygen

DO values ranged from 5.43 to 7.12 mg L^{-1} , which showed that the lake water is well oxygenated. The monthly values of DO ranged from 5.67 ± 0.16 mg L^{-1} in May to 6.84 ± 0.20 mg L^{-1} in February (Figure 2a). As expected, relatively high values were observed during the monsoon

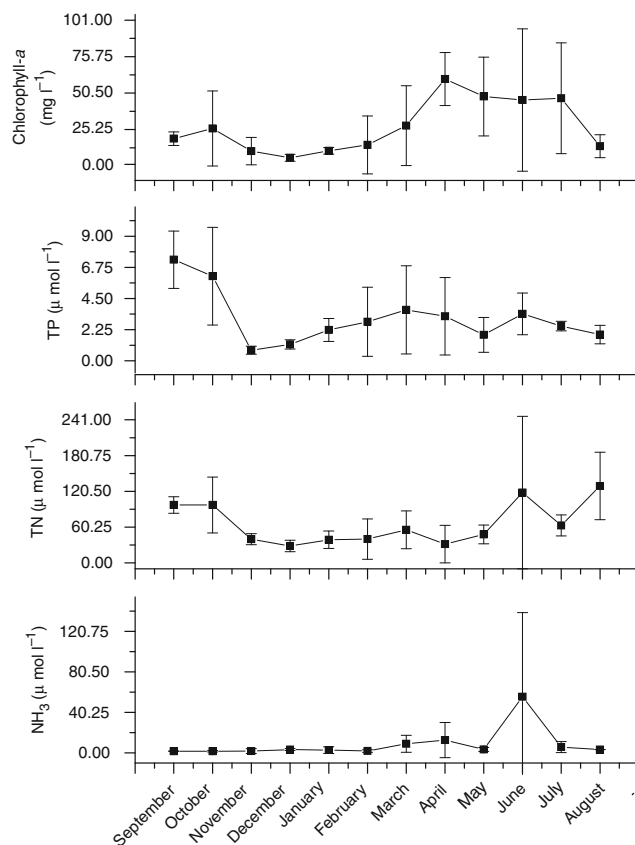
and post-monsoon period, which showed that freshwater influx from land runoff during monsoon, is one of the causative factors in variation in oxygen content of the lake water. Strong negative correlation ($p \geq 0.000$) of DO with salinity (conductivity) further supported the above observation. A moderate negative correlation ($p \geq 0.005$) was found between DO and chlorophyll-*a*, which showed that photo-synthetically re-sealed DO was negligible, and instead, the consumption of DO was higher in the presence of high algal biomass. This could be due to the near eutrophic conditions of the lake that support high algal growth, producing a high amount of organic matter in the form of senescent algae. A comparison of the present DO content with that of the pre-tsunami period (ranged from 5.0 to 7.4 mg l⁻¹) showed a marginal reduction, attributed to the increased salinity (conductivity) as solubility of oxygen and salt content are inversely related.

Nitrite and nitrate

Nitrite and nitrate were estimated together, considering the fact that nitrite is the most unstable nitrogenous nutrient that shows a wide range of fluctuations in aquatic ecosystems. The values ranged from 0.10 to 67.77 $\mu\text{mol l}^{-1}$ with monthly average values ranging from 0.38 ± 0.17 to $36.55 \pm 15.77 \mu\text{mol l}^{-1}$ during July and September, respectively (Figure 2a). A gradual decrease in concentration of these nutrients was observed from September to November, and an increase was noticed during the monsoon period. Wide fluctuation in inorganic nitrogen is well known in aquatic bodies and particularly in shallow ones. Nitrite, being the intermediate oxidation state between ammonia and nitrate, can appear as a transient species by the oxidation of ammonia or by the reduction of nitrate and also often released into the water as an extracellular product of the planktonic organisms (Santschi et al., 1990). However, nitrate is thermodynamically the most stable form of combined inorganic nitrogen in well-oxygenated waters. Variations in nitrate are generally a result of biologically activated reactions. Quick assimilation by phytoplankton and enhancement by surface runoff result in a large-scale spatiotemporal variation of nitrate in the aquatic medium (Zepp, 1997). Relatively high concentration of these nutrients during monsoon could be attributed to the nitrate-rich surface runoff getting into the lake. A significant increase (50-fold) in concentration of these nutrients was observed between the present values and that of the pre-tsunami concentration (0.24–0.64 $\mu\text{mol l}^{-1}$).

Ammonia

Ammonia concentrations ranged from 0.17 to 179.69 $\mu\text{mol l}^{-1}$, yielding monthly average values ranging from $1.71 \pm 0.23 \mu\text{mol l}^{-1}$ to $55.89 \pm 83.55 \mu\text{mol l}^{-1}$ during September and June, respectively (Figure 3). A significant variation was observed in its concentration throughout the year. A gradual increase was noticed from September to April with the peak concentration being observed during June, after which the concentration got



Tsunami Effect on a Coastal Lake in India, Figure 3 Seasonal variation in ammonia, total nitrogen, total phosphorous, and chlorophyll-*a* of Kokilamedu Lake during the study period (2006–2007).

reduced. In the present study, ammonia significantly contributed to TN concentration, as observed from its strong positive correlation ($p \geq 0.000$) with TN. Being the chief excretory product of the aquatic invertebrates, ammonia is also well known as a nutrient, which is preferred over nitrate by the phytoplankton community in certain environmental conditions. Thus, concentration of ammonia in the aquatic environment can be significantly affected by excretory release and utilization by phytoplankton (Gilbert et al., 1982). The irregular trend observed could be attributed to the above-mentioned two factors, along with the fact that in aquatic medium, it also gets oxidized and reduced to other forms; and hence, fluctuates widely (Sankaranarayanan and Qasim, 1969).

Total nitrogen

Concentration of TN ranged from 9.13 to 310.84 $\mu\text{mol l}^{-1}$. Monthly average values ranged from 31.70 ± 31.72 to $129.69 \pm 56.93 \mu\text{mol l}^{-1}$ (Figure 3). Relatively high TN concentration was observed during the pre-monsoon and summer than that of monsoon period. Significant decrease in the water level of the lake during pre-monsoon (to ~ 40% of the total volume present during monsoon)

leads to increase in concentration of dissolved nutrients. Positive correlation between TN and salinity (conductivity) supports the above observation. Among nitrogenous nutrients, contribution of ammonia to TN was more significant than the other two nitrogenous nutrients in this environment.

Silicate

Concentrations of silicate ranged from 17.33 to 247.50 $\mu\text{mol l}^{-1}$. Although no particular seasonal trend could be observed, its concentrations were relatively high during post-monsoon and summer. It did not show significant correlation with any nutrients except a strong positive correlation with chlorophyll-*a*. It is reasonable to presume that the phytoplankton population of the lake is perhaps dominated by species other than diatoms, which do not use silicate. Silicate concentration in aquatic environment can fluctuate due to several processes such as its biological removal by phytoplankton, especially by diatoms and silicoflagellates (Aston, 1980); factors like physical mixing of fresh water (Purushothaman and Venugopalan, 1972); adsorption of reactive silicate into suspended sedimentary particles (Lal, 1978); chemical interaction with sediment (Aston, 1980); and coprecipitation with humic compounds and iron (Stephns and Oppenheimer, 1972). Thus, the wide variation observed is not unusual. Present silicate values (ranged from 37.62 to 78.86 $\mu\text{mol l}^{-1}$) showed a fourfold increase as compared to the pre-tsunami observations. Release of silicate from the sediment which got deposited from sea during tsunami to water column takes place through a complex process wherein salinity and pH plays a significant role. Thus, the present environmental conditions might be favoring the benthopelagic coupling, resulting in the enhanced nutrient concentrations of the lake water.

Phosphate and total phosphorous

Phosphate and TP values ranged from 0.46 to 8.31 $\mu\text{mol l}^{-1}$ and 0.55 to 9.59 $\mu\text{mol l}^{-1}$, respectively. Concentration of phosphate and TP exhibited almost a similar pattern of variations. Both phosphate and TP showed strong positive correlations with nitrite + nitrate and TN; this showed that there was some external source of phosphate which could be in the form of bird droppings, as has been described by Venugopalan et al. (1998), that came along with the surface runoff during monsoon period. Though the peak was observed during September, relatively increased values of phosphate during December to March (monsoon and post-monsoon) supported the above-mentioned speculation of external input. Marginal increase in silicate with salinity (conductivity) is a result of impact of evaporation during the summer and pre-monsoon, as described earlier. Substantial increase in phosphate concentration (eightfold) was noticed during the post-tsunami period (pre-tsunami range 0.13–1.09 $\mu\text{mol l}^{-1}$). Phosphate-rich sediment brought

from sea during tsunami gets released to the water column depending on pH and salinity, as is known, and thus has hiked its content.

Chlorophyll-*a*

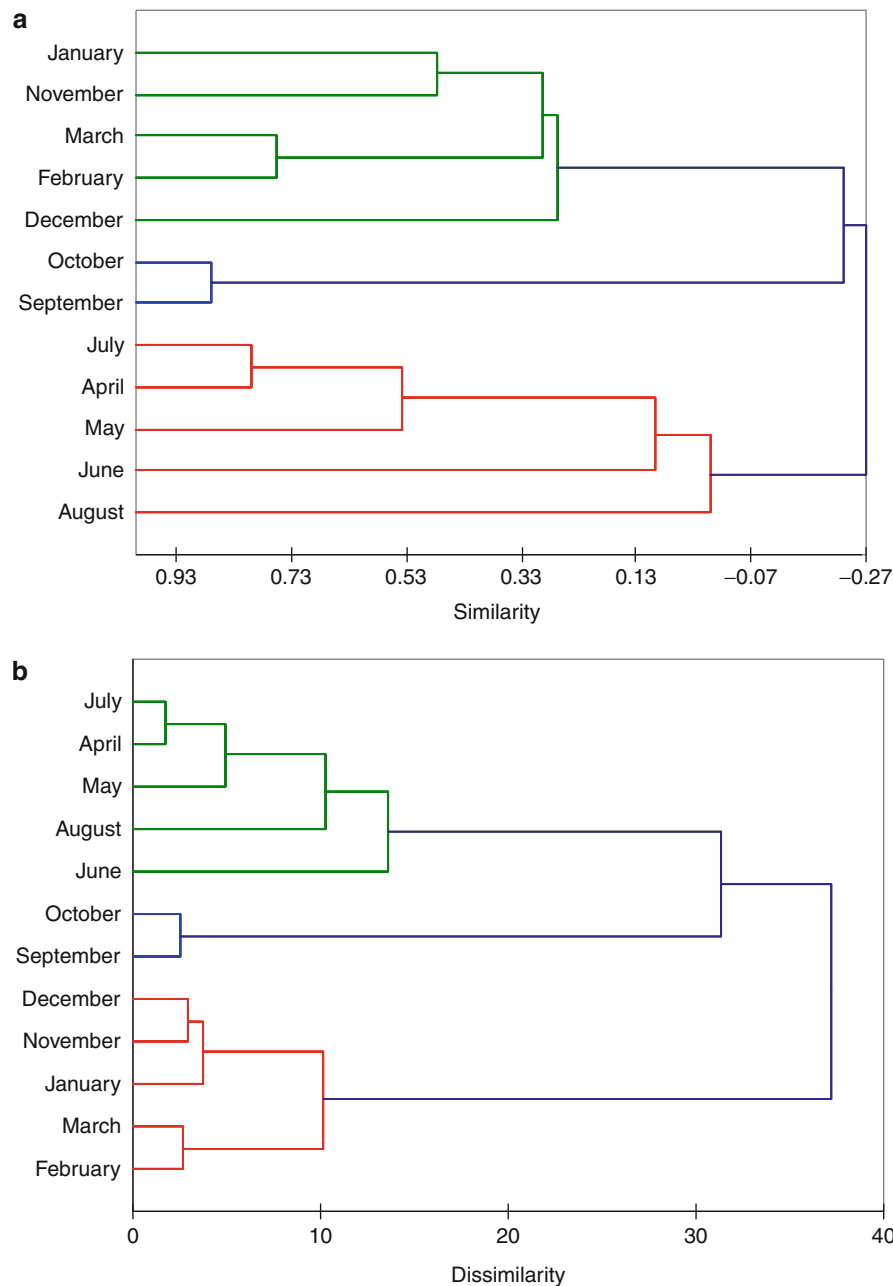
Chlorophyll-*a* values showed a well-marked variation and ranged from 2.24 to 115.78 mg m^{-3} during the present study, which indicated that the lake is highly productive in nature. The lowest value obtained during December could be due to the impact of freshwater input from land runoff during the northeast monsoon period. Moreover, relatively low salinity during this period also could have retarded the growth of brackish water phytoplankton species. Similarly, the higher value during April could be attributed to the optimum condition of phytoplankton growth with relatively high salinity, temperature, and pH. Chlorophyll-*a* was found to be positively correlated ($p \geq 0.005$) with salinity (conductivity) and pH. Moreover, during late summer, the decrease in water level of the lake concentrates the algal components. The chlorophyll-*a* values in combination with phosphate concentration is generally used to assess the trophic structure of the lake (Forsberg and Ryding, 1980). In the present study, the lake showed various trophic structures, such as mesotrophic, eutrophic, and hypertrophic, depending up on the different seasons of the year.

Cluster analysis

Results of cluster analysis showed that the same months were involved in their respective clusters in both similarity and dissimilarity clusters (Figure 4a, b). The months September and October formed one cluster, which represented the pre-monsoon period. November to March which represents the monsoon and post-monsoon period of this locality formed another cluster, which showed that there existed a similarity in environmental conditions of the lake during these months. The third cluster was formed from April to August, which represented a period corresponding to the summer and summer monsoon (southwest monsoon). The above observations showed that the lake environment is significantly affected by the northeast monsoon (winter monsoon) which is active in this part of India. The entire 1-year period is characterized by three clusters depicting three environmental conditions coinciding them.

Conclusion

High nutrient and chlorophyll-*a* concentrations observed implied that the lake is nearly eutrophic in nature. Pre- and post-tsunami water quality characteristics showed a drastic change in its environmental features, particularly the enhancement of nutrients. Since this lake is secluded from any kind of anthropogenic interventions and is of shallow depth, the internal nutrient loading from wind-induced resuspension could be another source of nutrient enrichment. In addition, sizable quantity of cattle excreta (about



Tsunami Effect on a Coastal Lake in India, Figure 4 Dendrogram of similarity (a) and dissimilarity (b) clusters among the different months.

200 numbers move around the lake) would have also contributed to the nutrient loading of the lake by a way of land runoff during monsoon period. The increasing water salinity (conductivity) is one of the main concerns which showed that the environment that existed nearly a decade ago is changing in the general process of transformation from a coastal shallow water lake into a salt marsh. In view of this, efforts are underway to deepen the lake by desilting it

and planting fruit-bearing and shady trees to improve the avian population. Although increased nutrient contents and decreased lake depth are substantial during the post-tsunami period, no fish kill has been observed, and the lake has not been eutrophic, as observed earlier (Venugopalan et al., 1998) at much lower nutrient concentration and higher water column. This suggests the need for further investigation on its ecology.

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Cross-references

Coastal Lagoons

TURBIDITY CURRENTS IN RESERVOIRS

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Introduction

Impounding and retaining water in reservoirs has been one essential basic development for the onset of human civilization. An important aspect, though, which has been

known for a long time and which has lately gained in importance, is reservoir sedimentation. Statistics show that more than 50% of streams and rivers are dammed, which implies that the greater part of transported sediment, in fact some 80%, is trapped in reservoirs. This corresponds to a volume of about 8–16 km³ (Lemperier and Lafitte, 2006). Morris and Fan (1998) quantified the world's total sediment deposit at between 15 and 40 Gt p.a.; this corresponds to between 0.5 and 1 t of sediment per 1,000 m³ of water. White (2001) estimates that more than 0.5% of the total reservoir storage volume is lost worldwide due to reservoir sedimentation. The costs for restoring these losses and rebuilding the dams can be estimated at US\$13 billion a year (Palmieri et al., 2003). Considering the different scales of reservoirs, it can be stated that for small reservoirs, the sediment budget can be managed within the framework of the operation rules and is considered as a routine job (e.g., water intakes). For reservoirs defined by great capacity with large dead-storage spaces, sedimentation is a long term rather than an acute phenomenon. The medium-sized reservoirs are characterized by sedimentation problems that need to be counteracted with adequate measures. Further, since these reservoirs are often operated on a daily or weekly basis, the relatively small available storage is intensively utilized. The most commonly applied methodologies for handling reservoir sedimentation are dredging and flushing activities (Palmieri et al., 2003). Dredging is costly and spatially a highly limited measure. Reservoir flushings are effective, but may, in fact, have substantial ecological impacts. Increased sediment concentrations downstream of dams may cause direct damage to fish populations and the macrozoobenthos while clogging off interstitial spaces in the gravel bed and evolving, thus, into substantial long-term problems.

Density currents

The force of gravity and small differences in density of water keep a density current in motion. In the case of lakes and reservoirs, the current is generated between different parts of the same fluid.

The differences in density can be triggered by:

- Temperature
- Salinity
- Concentration of suspended sediment (turbidity)

Figure 1, beneath, is a satellite image showing the mouth of the River Rhine in Lake Constance. The plunge point area (1) is clearly visible, and the plunging density current proceeding in a north-western direction from the mouth (2) is also clearly discernible. Schoklitsch (1935) described already the plunge of the River Rhine into Lake Constance, called “brech” by the local population, whereas that of the River Rhône into Lake Geneva was locally termed “la bataillière.”

Turbidity currents

Density currents are generally understood to refer to stratified flows caused by differences in density, whereas *turbidity currents* are specific forms and usually refer to stratified flows caused by differences in sediment concentration.

Depending on the density conditions in the lake or reservoir, Morris and Fan (1998) differentiate between three different turbidity flows:

- Top flow (overflow)
- Intermediate flow (interflow)
- Bottom flow (underflow)

Figure 2 depicts these possible flow situations plus the so-called plunge point or plunge line; this defines the



Turbidity Currents in Reservoirs, Figure 1 Satellite image of lake Constance showing plunge point and density current (Courtesy of Google, 2007).

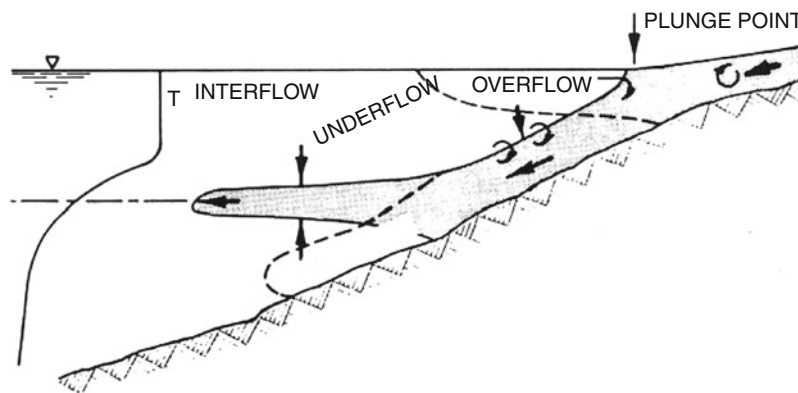
location where the inflow can be witnessed to disappear from the surface. Accumulations of driftwood and other flotsam caused by backflow have often been observed at such points.

Thus, turbidity currents are special density currents that arise from the plunging of the sediment-laden river water into the clear water of a lake or reservoir.

Understanding turbidity currents is of great importance as these may serve to throw light on the movement and, especially, on the deposition of fine sediment in reservoirs and lakes. The location of sediment deposition may be anticipated, thus, not only due to such classical phenomena as the reduction in flow velocity with its consequential sinking processes, but also due to the occurrence of density currents. A turbidity current developing at the bottom of a reservoir and moving toward the dam within the former streambed will come to a halt when it reaches the dam and will consequently deposit the suspended material. A phenomenon observed in many reservoirs is that fine sediment is mainly deposited near the intake structures in the vicinity of the dam.

The stability of turbidity currents depend on the geometry and slopes of a lake and on the differences in density of water. Turbidity currents can be dissolved, either continuously or in an enforced and accelerated manner on their way down.

Fundamentally, such density currents might be vented through a reservoir, if the local conditions are favorable, in order to minimize or even prevent the deposition of fine sediment. Buckley (1911) already described the occurrence of stratified flows caused by concentration differentials in the Indian storage pools as well as of the possibility of draining the turbid flood water flowing at depth by opening bottom outlets. Successful venting has also been described by Morris and Fan (1998) in the Lost Creek Reservoir in Oregon, USA, the Steeg Reservoir in Algeria, the Sefid-Rud Reservoir in Iran, and the Sanmenxia Reservoir in China, where it has been possible to sluice out more than half of the total sediment load through the reservoir during a flood. Xiaoqing (2003) mentioned the venting



Turbidity Currents in Reservoirs, Figure 2 Plunge point and possibilities of turbidity current development (Ford and Johnson, 1983).

of a turbidity current through the Nebeur reservoir in Tunisia, preventing, thus, more than 60% of the sediment from depositing. Some density currents have been observed to cover distances of more than 100 km of a reservoir on their way to the dam. One such example is Lake Mead, where a density current had been identified with a length of 150 km (Engez, 1961).

Reports on density currents were published by Cook and Richmond (2004) and Bühler et al. (2004). Molino et al. (2001) did not only describe density currents, but carried out also 2D numerical calculations. Firoozabadi et al. (2003) simulated density currents in physical model tests. Venting of density currents resulting from temperature gradients at the Whiskeytown Reservoir, California has been observed by Knoblauch and Simões (2000). Turbidity currents were studied by the EPFL in Lausanne, Switzerland (e.g., Oehy et al., 2000; De Cesare and Schleiss, 2004) with the aim of dispersing them in order to arrive at a more uniform sedimentation process in the Luzzzone reservoir and in Lake Lugano.

Example Soelk reservoir

The Soelk reservoir is located in the Grosssoelk river which is a southern tributary of the river Enns in Upper Styria, Austria. The natural catchment has an area of 140.9 km², and the three diverted catchments amount to a total of 244 km². The annual mean precipitation has been assessed around 1,194 mm; the mean flow of the Grosssoelk river at the reservoir is 5.23 m³/s; the annual flood has been calculated to be 42 m³/s; the calculated 10-year flood is 100 m³/s; and the 100-year flood is 165 m³/s (HL, 1975). The catchment area includes about 37% of forestland, 28% of alpine meadowland, and about 21% of land under agriculture – pastures and grassland (Bieringer, 1983). The remaining areas are rock, debris, roads, etc. The geology is typical for the Lower Tauern area, consisting mainly of the so-called gneiss complex. The gneiss compound material of the Central Alps is resistant, but the less stable mica schist is also prevailing in some places.

The Soelk power station, operated by Verbund Hydro Power AG (VHP), was built between 1976 and 1978. The design flow is 30 m³/s for a nominal head of 212 m. The maximum, or bottleneck, capacity is 61 MW, and the annual energy is 221 million kWh (Schneider, 2002).

The reservoir is created by an arch dam 39 m in maximum height and 129 m long at the crest. The reservoir is 1.3 km long and has a usable storage of 1.4 million cubic meters. A check dam 7 m high with a crest level of 899 m a.s.l. provided at the upstream end of the reservoir prevents coarse sediment from entering the reservoir. The auxiliary structures are all erected in the vicinity of the dam. The flood discharge is designed over the crest; the lowest outlet is situated on the right-hand bank, slightly downstream from the power intake. The flip-bucket outlet of the Donnersbach diversion is between the lowest outlet and the dam, and the outlet of the Klein-Soelk diversion is to the left of the reservoir.

In addition to the presence of a plunge point identified at the upstream end of the Soelk reservoir, there have been other indications suggesting the potential occurrence of turbidity currents. Sedimentation has its center near the dam, which may be the evidence of deposition from a turbidity lake caused by turbidity current. In addition, the design of the Soelk reservoir is excellently suited for the development of turbidity currents, as the reservoir is relatively short and straight and has a substantial gradient, the valley being V-shaped with steep slopes, and the bottom outlet being situated on the low level in the vicinity of the dam. Numerical analyzes indicate as well the occurrence of turbidity currents (Schneider, 2002, 2004).

In order to verify the assumption that turbidity currents occur in the Soelk reservoir and to obtain the best possible data for further numerical analysis, instruments were installed at five locations to measure hydrological parameters, which will be briefly described here and illustrated in Figure 3 (see also Badura, 2002; Habersack et al., 2002; Troy, 2006; Wachter, 2008; Gruber, 2009).

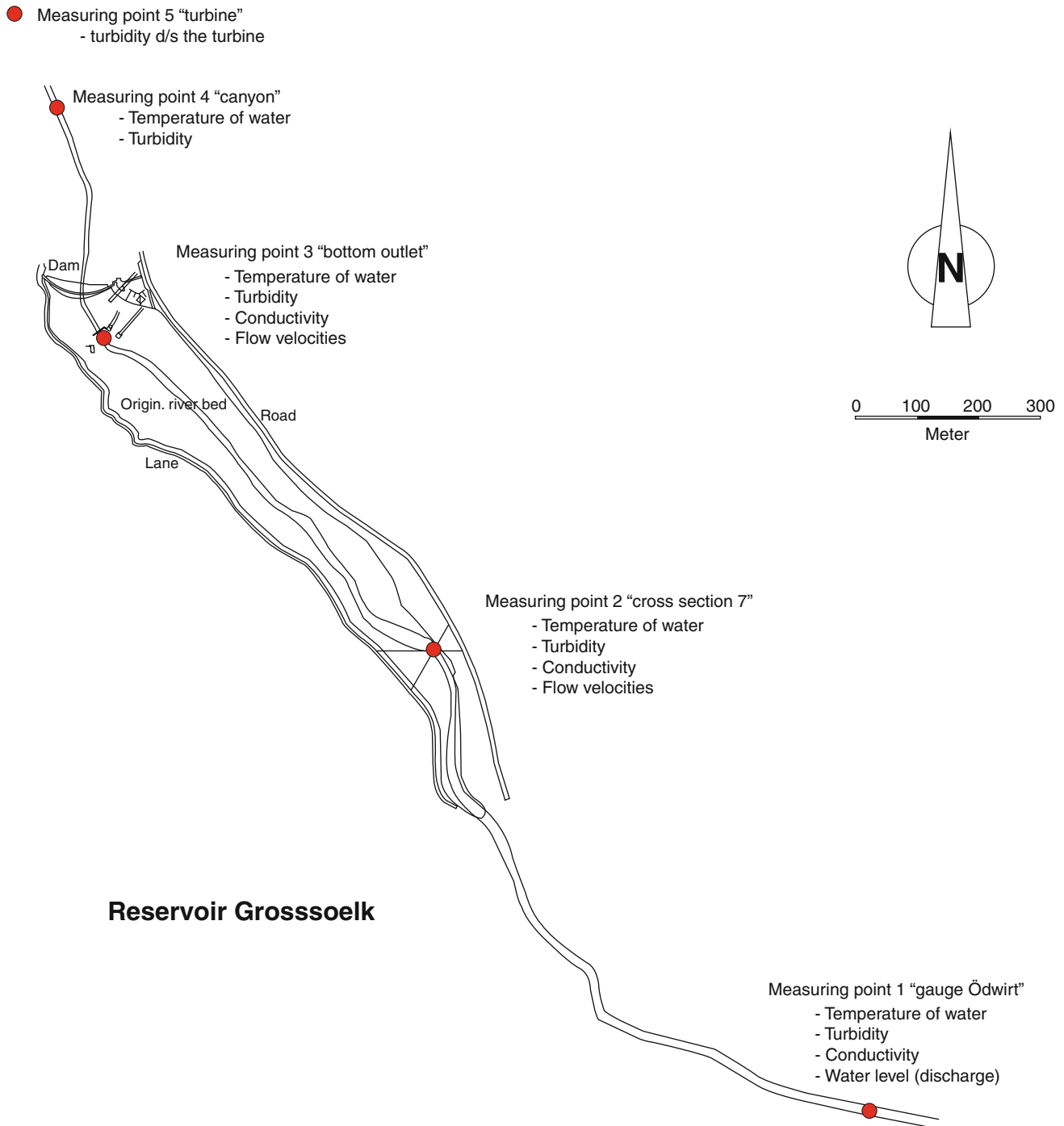
A temperature and turbidity probe (90° infrared backscatter) has been provided 1 km upstream from the reservoir head, near an existing discharge gauge, owned by the operator VHP with GSM data transmission (MP1).

The measuring device MP2 had been installed slightly downstream from the plunge point location. At about 7 m from the reservoir bottom, a facedown Acoustic Doppler Profiler (ADP), which measures flow velocities in three dimensions, had been installed. This ADP works at a frequency of 0.75 MHz and is capable of measuring cells with having a minimum size of 80 cm. Beneath these, two multiparameter probes had been located, 1 and 2.5 m above the bottom, measuring temperature, conductivity, and turbidity. The data were transmitted to the bank by cable and then via GSM. Near the data logger, a webcam has been observing the gauge.

A third instrument location (MP3) had been located immediately above the intake to the bottom outlet (Figure 4). It measures the same parameters as MP2; the ADP here had been installed directly on a cantilevering steel girder. Next to it was another tensioned vertical steel rope carrying the two multiparameter probes at 1 and 4 m above the bottom. These data were also transmitted to the surface by cable and then via GSM. A further webcam had been installed at this point.

The fourth measuring station (MP4) had been located a few hundred meters downstream from the dam, recording water temperature and turbidity. To portray an accurate overview of the reservoir in question, it has to be stated that there is usually no flow downstream the dam under dry weather conditions and that the probe measures data, thus, can only be collected in the case of spillway discharge or with the bottom outlet open. The fifth measuring station (MP5) had been installed downstream the turbine outlet at the powerhouse for measuring the turbidity of the water going through the turbine.

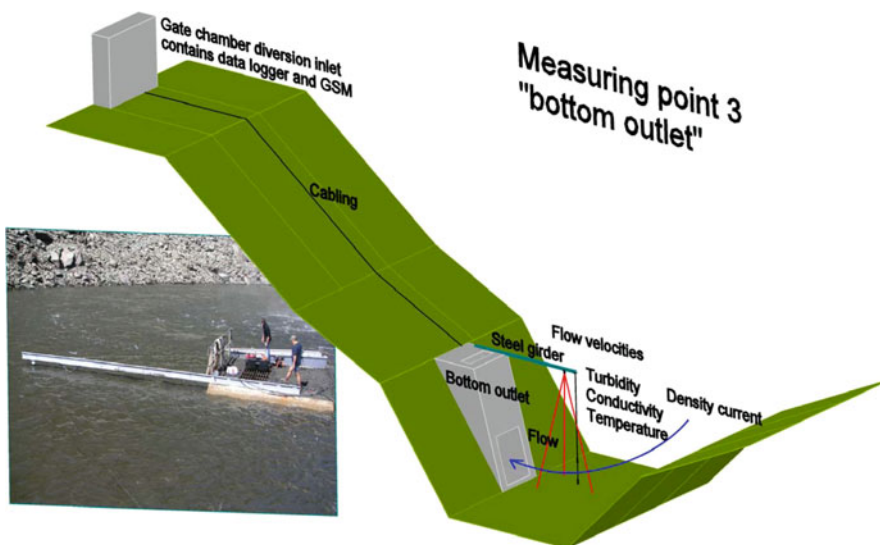
Figures 5 and 6 exemplify the flow situation in the reservoir during flood events. Figure 5 gives an impression of



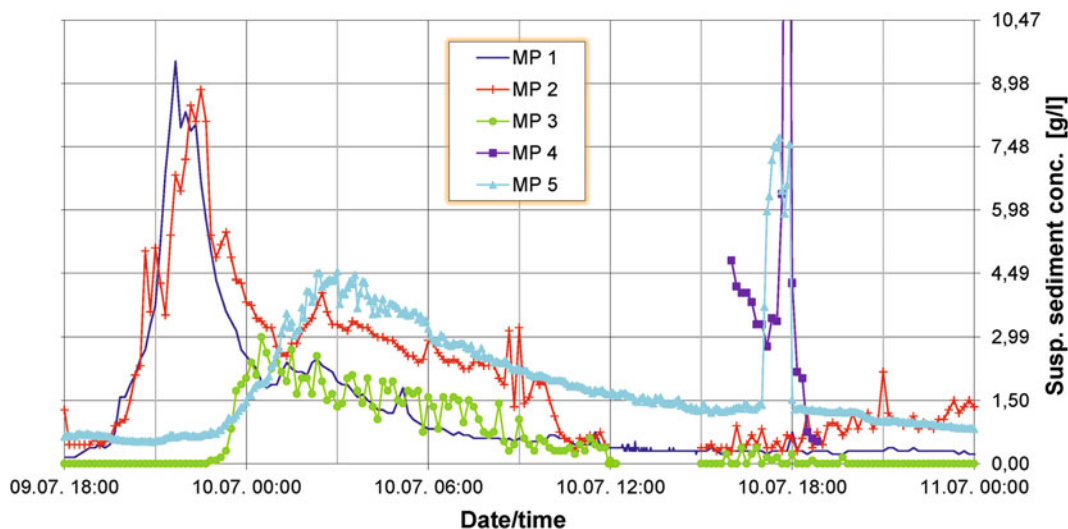
Turbidity Currents in Reservoirs, Figure 3 Measuring points at the Soelk reservoir, location and parameter.

the load curves and of the turbidity in different locations. It is evident that the inflowing water (MP1) shows the first peak. Due to the flow times between the different probes, a temporal different appearance of concentration peaks could be observed. The time lag between MP1 and MP2 has been 50 min and between MP2 and MP3, about 2 h.

Furthermore, a decrease of the peak has been visible in the vicinity of the dam. This indicates the intermixing of turbid and clear water. MP5 shows a similar characteristic as MP3, whereas the values for MP5 were generally higher than for MP3. This can be explained by the basic influence of the river Soelk that affects the probe.



Turbidity Currents in Reservoirs, Figure 4 Measuring point 3, probes and photo taken during installation, with the reservoir level drawn down.

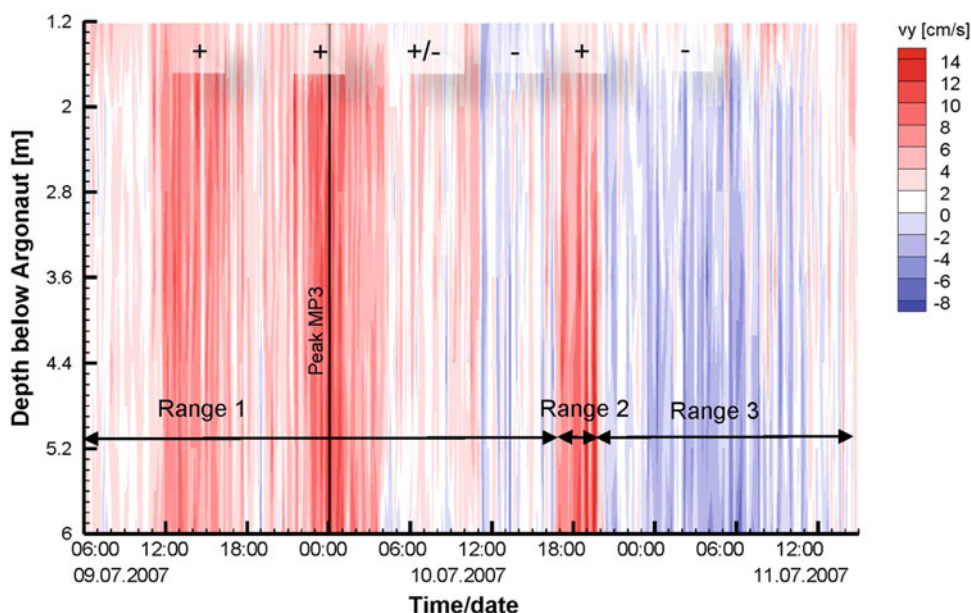


Turbidity Currents in Reservoirs, Figure 5 Load curve of suspended sediment concentration at different locations during a flood in July 2007.

However, the inflowing turbid water into the reservoir could be monitored specifically. The flood event in July 2007 was insofar characterized that the turbine had been shut down and the bottom outlet was opened for a short time at July 10. Between 17:00 and 18:30, the penstock had been shut and the bottom outlet was opened (until 19:30). Unfortunately, due to problems with the probe MP4, the first data are missing. However, it can be evidenced that the turbidity was relatively high due to the released water via spillway in the beginning. When

the bottom outlet had been opened, a rapid increase of the turbidity could be observed. After shutting the bottom outlet, these high concentrations disappeared again. The increase of turbidity at MP5 during the shutdown of the turbine can be explained by the influence of the river Soelk once more.

The measurements of velocities at MP3 orthogonal to the opening of the bottom outlet are depicted in Figure 6. Changes in flow velocities as well as flow directions could be observed. The shutting of the penstock and the opening



Turbidity Currents in Reservoirs, Figure 6 Velocities at MP3 during the flood event in July 2007 in y -direction (orthogonal to the opening of the bottom outlet).

of the bottom outlet can be seen here quite impressively. However, the velocities were very low and therefore the turbidity current was not fully developed.

Detailed studies regarding the economy involved in venting turbidity currents through the Soelk reservoir (Putz, 2007) have shown that this method of reservoir management is especially useful when water is discharged over the spillway as in the case of opening the bottom outlet; this entails not to minor water losses.

Summary

This entry summarizes the physical phenomenon turbidity currents described in literature as well as the field measurements taken in a European reservoir for verifying turbidity flows. It discusses also in consequence one possibility of reducing reservoir sedimentation. The example of the Soelk reservoir in Austria has been used for demonstration to prove that measurements in nature can give evidence that turbidity currents may flow downstream to the dam. As inflows to the reservoir and, hence, suspended sediment concentrations, have been low during the measurement campaign, there has been no evident event of venting turbidity currents. However, the identification of high sediment concentrations along the reservoir down to the bottom outlet during several events has substantiated the assumption that it is possible to vent turbidity currents through the Soelk reservoir during major events. Turbidity measurements above the reservoir head, directly below the plunge point region and at the bottom outlet, have revealed a time lag in the turbid flow peaks. This observation has been supported by the results of conductivity and temperature measurements. In addition, 3D measurements of flow velocity in the plunge

point region and at the bottom outlet brought forth satisfactory results even with low flow velocities.

In terms of statistics, the spillway operates six times a year. Thus, it should be possible to open the bottom outlet during floods in order to provide the basis for developing an important contribution to sustainable and environmentally compatible sediment management.

Acknowledgments

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Cross-references

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U

UDAIPUR, LAKES

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Introduction

In the sandy state of Rajasthan, there are numerous lakes in Udaipur. Surrounded by hills, Udaipur is located in a saucer-shaped basin over an area of 475.85 km² in the Aravalli range, at an elevation of 573 m. The city is interspersed with three serene lakes, Pichola, Fateh Sagar, and Udai Sagar, and is well known as the “City of Lakes.” These gleaming lakes enhance the beauty of the town. The two most scenic and famous lakes of the city are Lake Pichola and Lake Fateh Sagar. Lake Fateh Sagar lies to north of Pichola and was built by Maharana Jai Singh, but it got the name of Fateh Singh who rebuilt its dam. Both the lakes are breathtakingly beautiful, and one can take a cruise on their waters. The sunset over these lakes is momentous to be cherished.

Pichola is fed by Sisarma, a non-perennial river. Gorana-ki-nal, a dam upstream the Aravalli, was connected to the Sisarma river recently. Fateh Sagar has a very small catchment of its own and is fed by Bari tank and Chota and Bada Madar. The overflow from the Bada and Chota Madar tanks merge with the Ahar river. The Ahar river feeds Udai Sagar several kilometers downstream. The overflow from Bari tank directly merges with Fateh Sagar. The overflow from Pichola flows into Fateh Sagar, and the overflow from Fateh Sagar flows into the Ahar through a canal before it enters Udai Sagar. With this

web of lakes and wells, most of the rain falling within the Udaipur basin was kept within the basin itself, with very little losses.

In the past few decades, catchment destruction has increased the rate of siltation, jeopardizing the very existence of the lakes. Deforestation in the hills surrounding Udaipur and in the adjoining forests of Mewar region has meant that each year’s monsoon washes down tons of silt into the lakes. It has been estimated that the capacity of Pichola is reducing every year by 0.93%, and that of Fateh Sagar, by 1.16%. There was a silt trap between the Madar tank and Fateh Sagar at Thur-ki-pal village, but it has now broken. The silt now enters into the Fateh Sagar. Urbanization around the lakes has turned them into receptacles for organic matter and domestic wastes.

Approximately 60,000 people live around the lakes, and nearly 60 hotels dot their peripheries. Domestic sewage and wastewater from the hotels is let into these lakes. Domestic solid waste of about 20–25 t/day is also dumped close to the lakes. This finds its way into the lakes during the monsoons. Besides, people living around the lakes continuously attempt to extend their personal property by encroaching upon the lakes. The 73 ghats on Lake Pichola are used by the public for bathing and washing, which includes infected linen from hospitals. A large amount of detergent goes into the water, increasing its phosphate content. The poor quality of drinking water here is resulting in the high incidence of water-borne diseases such as typhoid, paratyphoid, amoebic dysentery, colitis, diarrhea, and viral hepatitis. The pollution has also practically wiped out the major carps, leaving only minor carps, minnows, and puntius.

Between 1978 and 1982 a partial sewage system was constructed (without a sewage treatment plant) to cover 30–35% of the population around the lakes. However, due to certain design limitations and improper maintenance, the system does not function and raw sewage flows directly into Pichola. Besides, water treatment plants,

which have a capacity of 24.1 million liters per day (mld), generally treat 31.8 mld – handling an overload of 32%. A number of cracks in the filter beds result in suspended solids escaping into the drinking water.

Lake Pichola

Pichola Lake is a beautiful expanse of water that surrounds the islands of the Lake Palace Hotel (Jag Niwas) and Jag Mandir. The backdrop of the overlooking City Palace gives this lake its name – Pichola. Apart from this there is also another origin to its name. It is said that the name comes from the nearby small village of Picholi and was originally created early in the fifteenth century by a local Banjara tribesman who transported grain. Legend has it that, finding his bullocks could not ford the stream at the southern end, he built a dam across it, over which the animals could cross.

In 1560, a year after Maharana Udai Singh II began building his new capital of Udaipur around the shore, he strengthened the dam and greatly enlarged the lake. Apart from the two large islands, there are several smaller ones, among them are Arsi Vilas, which is a haven for birds, and a platform, Natni-ka-Chabutra, which has its own legend. At the northern end of the lake is the old town with its ghats and a ceremonial ghat where the Gangaur Festival is celebrated with fireworks and illuminations. The height of the dam is 15.24 m in the Badi Pol area.

Along its eastern shore sprawls the massive City Palace. South of this is the hill known as Machhala Magra, where part of the old city wall and the small fort of Eklinggarh could still be seen. Beyond this is the Shikarbadi Hotel, once the Khasi Odi, or hunting lodge, of the Maharanas. At full tank level the Pichola Lake covers an area of almost 1.5 sq km. The beautiful Lake Pichola is surrounded by hills, palaces, temples, and bathing ghats. It is the largest of all Udaipur Lakes.

Fateh Sagar Lake

The pride of the City of Lakes, this lake was constructed toward the north of Lake Pichola and was built by Maharana Jai Singh, but it got the name of Fateh Singh who rebuilt its dam. Fateh Sagar is the second of Udaipur's four man-made lakes. During 1678, Maharana Jai Singh (1680–1698), who had already constructed the famous Jaisamand Lake southeast of Udaipur, excavated this new small lake. It lies immediately to the north of and connected by a canal to Pichola Lake, which had been established by Maharana Udai Singh II a century earlier.

Fateh Sagar is 2.4 km long, 1.6 km wide, and 11.5 m at its deepest point; when full, it covers an area of about 1 sq km, being fed by the Ahar (Berach) river. It is possible to drive around the complete circumference of the lake via Moti Magri Road, Fateh Sagar Drive, and Rani Road, a serpentine route that provides beautiful views of the lake as well as the encircling Aravalli Hills. The main causeways to the lake are from Pichola Lake, Madar Lake, and Badi Lake. It has three inlet channels and an overflow channel for the rainy season.

Two centuries after its construction, a severe storm and heavy rainfall collapsed the old eastern embankment causing loss of life and considerable damage, especially to the nearby, lower-level Sahelion-ki-Bari gardens. In 1889, to prevent further such flooding, Maharana Fateh Singh reconstructed the embankment. Later that same year, the Duke of Connaught, third son of Queen Victoria, laid the new embankment's foundation stone, and the lake was renamed Fateh Sagar. This reconstructed northeastern embankment has three names, the Pal, the Drive, or Connaught Bund (embankment or breakwater). Along it is the entrance to Moti Magri hill, on the summit of which is a landscaped park with the Maharana Pratap Memorial.

Three small islands grace Fateh Sagar, the largest being Nehru Park, a popular garden island with a restaurant and zoo, which is reached by inboard motor boats from the bottom of Moti Magri Hill. The Government of Rajasthan made the second island into a public park with a spectacular water-jet fountain, and the third houses the Udaipur Solar Observatory, the largest in Asia. A peaceful spot not far from the city center, the lake is a popular leisure area for picnics and water recreation in hired pedal boats. Because of Fateh Sagar's blue waters and its backdrop of green hills, it is often referred to as the second Kashmir, an epithet often given to all of Udaipur.

Cross-references

[Indian Lakes](#)

UNITED KINGDOM, LARGEST LAKES

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Introduction

The United Kingdom has a population of some 63 million and an area of 244,000 km² of which inland waters cover an area of over 3,000 km² giving a high proportion of population to areas of land and inland waters.

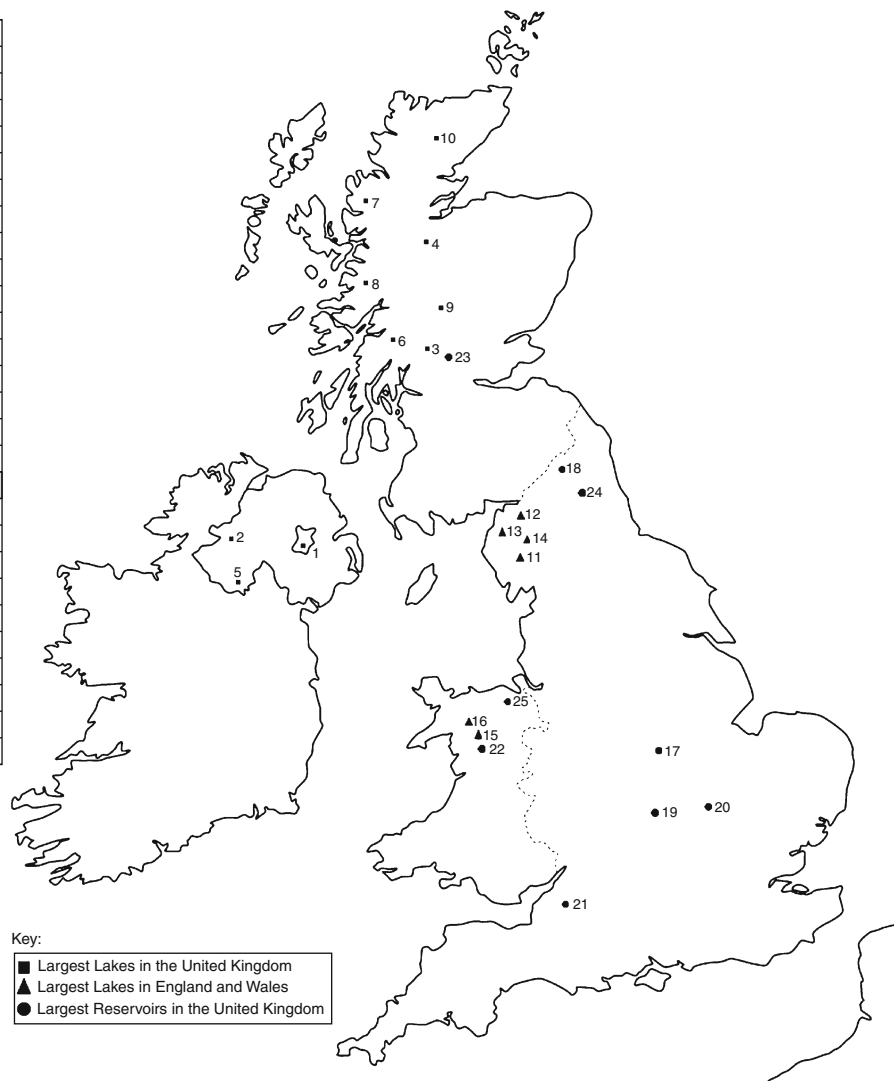
It is estimated that there are some 50,000 lakes in the United Kingdom of which over 31,000 are in mainland Scotland alone. These are mainly found in the Highlands where, in the Counties of Sutherland and Caithness, they form an area commonly known in scientific geography as the "Flow Country," since their density forms a large proportion of the surrounding land area. In general these highland lakes may only have local names, often in Gaelic and most are shallow and under 5 ha (0.05 km²). The larger of these are of glacial formation.

In Scotland lakes are known as *lochs* and sometimes *lochans*. *Loch* is a Scottish Gaelic word for a lake or fiord from the Irish *lough* which itself is formed from Irish Gaelic *loch* pronounced "loc."

In Wales, "lake" is translated from the Welsh as "Llyn."

The following tables provide a summary of the largest lakes in the United Kingdom. Their location is shown in [Figure 1](#).

No	Lake	Location
1	Lough Neagh	Northern Ireland
2	Lower Lough Erne	Northern Ireland
3	Loch Lomond	Scotland
4	Loch Ness	Scotland
5	Upper Lough Erne	Northern Ireland
6	Loch Awe	Scotland
7	Loch Maree	Scotland
8	Loch Morar	Scotland
9	Loch Tay	Scotland
10	Loch Shin	Scotland
11	Windermere	England
12	Ullswater	England
13	Bassenthwaite Lake	England
14	Derwent Water	England
15	Llyn Vyrnwy	Wales
16	Llyn Bala	Wales
No	Reservoirs	Location
17	Rutland Water	United Kingdom
18	Kielder Water	United Kingdom
19	Pitsford Water	United Kingdom
20	Grafham Water	United Kingdom
21	Chew Valley Lake	United Kingdom
22	Trawsfynydd	United Kingdom
23	Carron Valley	United Kingdom
24	Derwent Reservoir	United Kingdom
25	Llyn Brenig	United Kingdom



United Kingdom, Largest Lakes, Figure 1 Largest lakes and reservoirs in the United Kingdom.

- Largest in area and volume
- Largest in England
- Largest in Wales
- Largest reservoirs

6	Loch Awe	1.20	39	Scotland
7	Loch Maree	1.09	29	Scotland
8	Loch Morar	2.30	27	Scotland
9	Loch Tay	1.60	26	Scotland
10	Loch Shin	0.35	23	Scotland

Largest lakes in the United Kingdom

	Lake	Volume (km ³)	Area (sq km)	Location
1	Lough Neagh	3.52	381	Northern Ireland
2	Lower Lough Erne	1.30	105	Northern Ireland
3	Loch Lomond	2.60	71	Scotland
4	Loch Ness	7.40	57	Scotland
5	Upper Lough Erne	0.35	43	Northern Ireland

Largest lakes in England

	Lake	Volume (km ³)	Area (sq km)
1	Windermere	0.31	14.70
2	Ullswater	0.20	8.90
3	Bassenthwaite Lake	0.11	5.10
4	Derwent Water	0.03	5.30

Largest lakes in Wales

	Lake	Volume (km ³)	Area (sq km)
1	Llyn Vyrnwy	0.06	8.20
2	Llyn Bala	0.02	4.40

Largest reservoirs in the United Kingdom

	Lake	Volume (km ³)	Area (sq km)	Location
1	Rutland	0.12	12.6	England
2	Kielder Water	0.20	11.0	England
3	Pitsford Water	0.02	7.40	England
4	Grafham Water	0.05	7.40	England
5	Chew Valley Lake	0.02	4.90	England
6	Trawsfynydd	0.03	4.80	Wales
7	Carron Valley	0.02	3.90	Scotland
8	Derwent Reservoir	0.05	3.70	England
9	Llyn Brenig	0.05	3.70	Wales

Deepest lake

The deepest lake in the United Kingdom is Loch Morar with a maximum depth of 309 m, followed by Loch Ness at 228 m.

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Cross-references

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[English Lakes](#)

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[Lough](#)

[Lough Neagh](#)

[Reservoirs in Great Britain](#)

UNITED STATES: PRINCIPAL FRESHWATER LAKES

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Introduction

The United States has some 250 freshwater lakes that are known to have surface areas of 10 sq miles (26 km²) or more. Nearly 100 of these are in Alaska and 100 in Minnesota, Wisconsin, Michigan, New York, and Maine. Thirty-four freshwater lakes, exclusive of the Great Lakes, are known to have maximum depths of 250 ft (76.2 m) or more. Twenty of these are in Alaska, and Alaska undoubtedly has more lakes of that depth which have not been sounded.

In actual fact, the amount of water stored in natural lakes in the United States, even exclusive of the Great Lakes, is much greater than the amount stored in artificial lakes (reservoirs). With the exception of the Great Lakes, however, the economic value of natural lakes is surpassed by that of reservoirs. Natural lakes are best known in the United States for the recreational advantages they afford.

United States: Principal Freshwater Lakes, Table 1 Natural freshwater lakes of 10 sq miles (26 km²), excluding the Great Lakes, arranged by US states

Name	Latitude	Longitude	Area (sq miles)
Alaska			
Iliamna	59°35	155°00	1,000
Becharof	57°50	156°25	458
Teshkepuk	70°35	153°30	315
Naknek	58°35	156°00	242
Tustumena	60°25	150°20	117
Clark	60°10	154°00	110
Dall	60°15	163°45	100
Inland ^a	66°30	159°50	95
Imuruk Basin ^a	65°05	165°40	80
Upper Ugashik	57°50	156°25	75
Kukaklek	59°35	155°00	72
Lower Ugashik	57°30	156°55	72
Nerka	59°20	158°45	69
Nuyakuk	59°50	158°50	64
Aropuk	61°10	163°45	57
Tazlina	61°50	146°30	57
Nanwhyenuk or Nonvianuk	59°00	155°25	56
Nunavakpak	60°45	162°40	53
Kaghasuk ^a	60°55	163°40	52
Skilak	60°25	150°20	38
Chauekuktuli	60°05	158°50	34
Chikuminuk	60°15	158°55	34
Beverly	59°40	158°45	33
Whitefish	61°20	160°00	33
Aleknagik	59°20	158°45	31
Brooks	58°30	155°55	31
Kgun	61°35	163°50	31
Nonvianuk	59°00	155°30	31
Takslesuk	61°05	162°55	31

United States: Principal Freshwater Lakes, Table 1 (Continued)

Name	Latitude	Longitude	Area (sq miles)
Susitna	62°25	146°40	10
Unnamed	60°20	162°00	10
Unnamed	60°25	162°00	10
Unnamed	60°55	162°10	10
Unnamed	59°55	163°15	10
Unnamed	62°00	162°00	10

Name	County	Area (sq miles)
California		
Tahoe ^b	Placer, Eldorado	193
Clear	Lake	65
Eagle ^c	Lassen	41
Florida		
Okeechobee	Hendry, Glades, Okeechobee, Martin, Palm Beach	700
George	Putnam, Marion, Volusia, Lake	70
Kissimmee	Osceola, Polk	55
Apopka	Orange	48
Istokpoga	Highlands	43
Tsala Apopka	Citrus	30
Tohopekaliga	Osceola	29
Harris	Lake	27
Orange	Alachua, Marion	26
East Tohopekaliga	Osceola	19
Griffin	Lake	14
Monroe	Seminole, Volusia	14
Jessup	Seminole	13
Weohyakapka	Polk	12
Talquin	Gadsden, Leon	11
Eustis	Lake	11
Blue Cypress	Osceola, Indian River	10
Hatchineha	Polk, Osceola	10
Lochloosa	Alachua	10
Idaho		
Pend Oreille	Bonner	148
Bear ^d	Bear Lake	110 ^e
Coeur d'Alene	Kootenai	50
Priest	Bonner	37
Grays ^f	Bonneville, Caribou	34
Henrys	Freemont	10
Iowa		
Spirit	Dickinson	12
Louisiana		
White ^g	Vermilion	83
Grand	Iberia, St Mary, St Martin	64
Caddo ^h	De Soto	60
Catahoula ^t	La Salle	32
Grand	Cameron	32
Six Mile	St Martin	30
Fausse Pointe	St Mary, Iberia	24
Lac des Allemands	St John the Baptist	23
Verret	Assumption	22
Polourde	St Martin, St Mary, Assumption	18
Maine		
Moosehead	Piscataquis, Somerset	117
Sebago	Cumberland	45
Chesuncook ^u	Piscataquis	43

United States: Principal Freshwater Lakes, Table 1 (Continued)

Name	Latitude	Longitude	Area (sq miles)
George	61°15	148°35	29
Nunavak Anukslak	61°05	162°30	29
Unnamed	60°55	164°00	28
Grosvenor	58°40	155°15	27
Tetlin	63°05	142°45	27
Kakhomak	59°30	154°10	12
Karluk	57°20	154°05	12
Mother Goose	57°10	157°20	12
Unnamed	60°25	164°10	12
Unnamed	59°50	163°25	12
Unnamed	62°15	162°20	12
Unnamed	70°50	153°30	12
Coleville	58°45	155°40	11
Harlequin	59°25	138°55	11
Unnamed	60°25	164°10	11
Unnamed	60°55	162°20	11
Bear	56°00	160°15	10
Chignik	56°15	158°50	10
Chakachamna	61°10	152°30	26
Imuruk	65°35	163°10	26
Nunavakanuk	62°05	164°40	25
Louise	62°20	146°30	23
Minchumina	63°55	152°15	23
Klutina	61°40	145°30	22
Unnamed	61°30	164°30	22
Unnamed	71°05	156°30	21
Beluga	61°25	151°30	20
Unnamed	60°05	164°00	20
Unnamed	61°40	160°25	20
Kenai	60°25	149°35	19
Kyigayalik	61°00	162°30	19
Tikchik	59°55	158°20	19
Bering	60°20	144°20	17
Kulik	59°50	158°50	17
Upnuk	60°05	158°55	17
Unnamed slough	62°40	163°30	17
Teloquana	60°55	153°55	16
Unnamed	60°30	161°40	16
Unnamed	61°00	163°45	16
Unnamed	61°30	164°55	16
Five Day Slough	62°05	162°00	15
Togiak	59°35	159°35	15
Unnamed	59°55	163°15	15
Black	56°25	159°00	14
Ualik	59°05	159°30	14
Walker	67°05	154°25	14
Unnamed	60°20	164°25	14
Unnamed	60°50	163°30	14
Unnamed	59°50	163°30	14
Amanka	59°05	159°10	13
Whitefish	60°05	154°55	13
Unnamed	71°00	156°00	13
Crosswind	62°20	146°00	12
Ewan	62°25	145°50	10
Kontrashibuna	60°10	154°00	10
Kukaklik	61°40	160°30	10
Kulik	58°55	155°00	10
Unnamed	61°45	160°40	10
Miles	60°40	144°45	10

United States: Principal Freshwater Lakes, Table 1 (Continued)

Name	County	Area (sq miles)
West Grand	Washington	37
Flagstaff	Somerset, Franklin	28
Spednik ^v	Washington	28
Grand Falls ^v	Washington	27
East Grand ^v	Washington, Aroostook	26
Mooselookmeguntic	Oxford, Franklin	26
Twin	Penobscot, Piscataquis	25
Chamberlain & Telos	Piscataquis	22
Graham	Hancock	19
Churchill and Eagle	Piscataquis	17
Baskahegan	Washington	16
Umbagog ^o	Oxford	16
Brassua	Somerset	15
Square	Aroostook	14
Millinocket	Penobscot,	14
	Piscataquis	13
Great	Kennebec Oxford	13
Richardson	Piscataquis	11
Schoodic	Piscataquis	11
Sebec	Oxford	10
Aziscohos	Somerset	10
Canada Falls	Oxford	10
Rangeley		10
Michigan		
St. Clair ⁱ		460
Houghton	Roscommon	31
Torch	Antrim, Kalkaska	29
Charlevoix ^j	Charlevoix	27
Burt	Cheboyen	27
Mullet	Cheboyen	26
Gogebic	Ontonagon, Gogebic	21
Manistique	Mackinac, Luce	16
Black	Cheboyen, Presque Isle	16
Crystal	Benzie	15
Portage	Houghton	15
Higgins	Crawford, Roscommon	15
Hubbard	Alcona	14
Leelanau	Leelanau	13
Indian	Schoolcraft	12
Elk	Antrim, Grand Traverse	12
Glen	Leelanau	10
Minnesota		
Lake of the Woods ^k	Lake of the Woods	1485
Upper and Lower Red	Beltrami	451
Rainy ^k	Koochiching, St Louis	345
Mille Lacs	Aitken, Crow Wing, Mille Lacs	207
Leech	Cass	176
Winnibigoshish	Itasca, Cass	109
Vermilion	St Louis	77
Lac La Croix ^k	St Louis	53
Cass	Cass, Beltrami	46
Basswood ^k	Lake	46
Namakan ^k	St Louis	44
Kabetogama	Itasca	40
Pepin ⁱ	Goodhue, Wabasha	39

United States: Principal Freshwater Lakes, Table 1 (Continued)

Name	County	Area (sq miles)
Mud	Marshall	
Saganaga ^k	Cook	37
Pokegama	Itasca	32
Minnetonka	Hennepin, Carver	24
Otter Tail	Otter Tail	22
Gull	Cass,	22
	Crow Wing	20
Pelican	St Louis	
Traverse ^w	Traverse	19
Big Stone ^w	Big Stone	18
Crooked ^k	St Louis, Lake	17
Sandy	Aitkin	17
Swan	Nicollet	15
Island	St Louis	15
Bowstring	Itaska	14
Burntside	St Louis	14
Sand Point ^k	St Louis	14
Trout	St Louis	14
St Croix ^l	Washington	14
Lac qui Parle	Chippewa,	13
	Lac qui Parle	13
Pelican	Crow Wing	
Dead	Otter Tail	13
Minnewaska	Pope	12
Thief	Marshall	12
Nett	St Louis, Koochiching	12
Osakis	Douglas, Todd	10
Bemidji	Beltrami	10
Lida	Otter Tail	10
Montana		
Flathead	Lake, Flathead	197 ^m
Medicine	Sheridan	15 ⁿ
McDonald	Flathead	10
Nevada		
Tahoe ^b	Ormsby	193
New Hampshire		
Winnepesaukee	Belknap, Carroll	72
Umbagog ^o	Coos	16
Squam	Grafton, Carroll	11
New York		
Champlain ^p	Clinton, Essex	490 ^q
Oneida	Oswego, Oneida	80
Seneca	Seneca, Schuyler	67
Cayuga	Cayuga, Seneca, Tompkins	66
George	Warren	44
Chautauqua	Chautauqua	21
Black	St Lawrence	17
Canandaigua	Ontario, Yates	17
Skaneateles	Onondaga, Cayuga	14
Owasco	Cayuga	10
North Carolina		
Mattamuskeet ^r	Hyde	67
Phelps	Washington	25
Waccamaw	Columbus	14
Oregon		
Upper Klamath	Klamath	142 ^s
Crater	Klamath	
South Dakota		

United States: Principal Freshwater Lakes, Table 1 (Continued)

Name	County	Area (sq miles)
Traverse ^w	Roberts	18
Big Stone ^w	Roberts	17
Tennessee		
Reelfoot	Lake, Obion	22
Texas		
Caddo	Marion	60
Utah		
Utah	Utah	140
Bear ^d	Rich	110
Vermont		
Champlain	Chittenden, Franklin	490 ^q
Washington		
Chelan	Chelan	55
Washington	King	35
Ozette	Clallam	12
Wisconsin		
Winnebago	Winnebago, Calumet, Fond du Lac	215
Pepin ^l	Pierce, Pepin	39
Poygan	Winnebago	17
Koshkonong	Jefferson	16
Mendota	Dane	15
St Croix ^l	St Croix	12
Green	Green Lake	11
Wyoming		
Yellowstone	Yellowstone National Park	137 ^x
Jackson	Teton	39 ^y
Shoshone	Yellowstone National Park	11

Note: 1 sq mile = 2.59 km²^aMay be saltwater^bCalifornia and Nevada^cMildly saline, less than 1,000 ppm^dIdaho and Utah^e136 sq miles including Mud Lake^fSubmerged marsh^gOriginally brackish; now kept fresh by controls on saltwater intrusion^hLouisiana and TexasⁱMichigan and Ontario^jFormerly called Pine^kMinnesota and Ontario^lMinnesota and Wisconsin^mAt normal high water; 188 sq miles at medium low water; lake regulated for power between these limitsⁿIncludes four islands having area of about 1 sq miles^oMaine and New Hampshire^pNew York, Vermont, and Quebec^qIncludes islands totaling about 55 v sq miles^rThe lake originally landlocked, was drained and provided with outlet and is freshwater; level regulated to some extent by control works on canals draining the area^sAt upper level; dam at outlet allows regulation so that area varies between 93 and 142 sq miles^tShrinks to small area at extremely low stages^uIncludes Ripogenus and Caribou^vMaine and Quebec^wMinnesota and South Dakota^xIncludes islands totaling 3 sq miles^yEnlarged by dam; original area, 30 sq miles**United States: Principal Freshwater Lakes, Table 2** Natural freshwater lakes 250 ft deep or more, ranked by depth

Name	Location	Depth (ft)
Crater ^a	Oregon	1,932
Tahoe ^b	California and Nevada	1,645
Chelan	Washington	1,605
Pend Oreille	Idaho	1,200
Nuyakuk ^c	Alaska	930
Deer ^{d, e}	Alaska	877
Chauekuktuli ^c	Alaska	700
Crescent ^{d, f}	Washington	624
Seneca	New York	618
Clark ^c	Alaska	606
Beverley ^c	Alaska	500
Nerka ^c	Alaska	475
Tokat ^{d, e}	Alaska	474
Long ^{d, e}	Alaska	470
Lower	Alaska	459
Sweetheart ^{d, e}		
Cayuga ^g	New York	435
Crater ^{d, e}	Alaska	414
Cooper ^{d, e}	Alaska	>400
Champlain	New York, Vermont, Quebec	400
Kasnyu	Alaska	393
Chakachamna	Alaska	380
Ozette	Washington	331
Aleknagik	Alaska	330
Sebago	Maine	316
Swan	Alaska	>314
Baranoff	Alaska	303
Payette	Idaho	>300
Quinalt	Washington	about 300
Crescent	Alaska	291
Wallowa ^{d, h}	Oregon	283
Chilkoot	Alaska	282
Odell ^{d, i}	Oregon	279
Silver	Alaska	278
Grant	Alaska	>250

Note: 1 sq mile = 2.59 km²

Note: Pyramid Lake, a saline lake in Nevada (see p. 14) is about 280 ft deep at its present level, according to M. T. Wilson (written communication, 1962)

^aSounded by US Coast and Geodetic Survey in 1959. In 1886, Mark Kerr measured 1,996 feet at approximately same point. According to Hutchinson (1957), Crater Lake is the second deepest lake in the Western Hemisphere, exceeded only by Great Slave Lake in Canada, depth about 2,010 ft^bRussell (1885, p. 72)^cInterim report on southwestern Alaska, by the Corps of Engineers, 1954^dLess than 10 sq miles^eSounded by US Geological Survey^fWolcott (1961)^gFenneman (1938)^hW. D. Smith, Northwest Science, December 1939ⁱSounded by K. N. Phillips, August 10, 1940

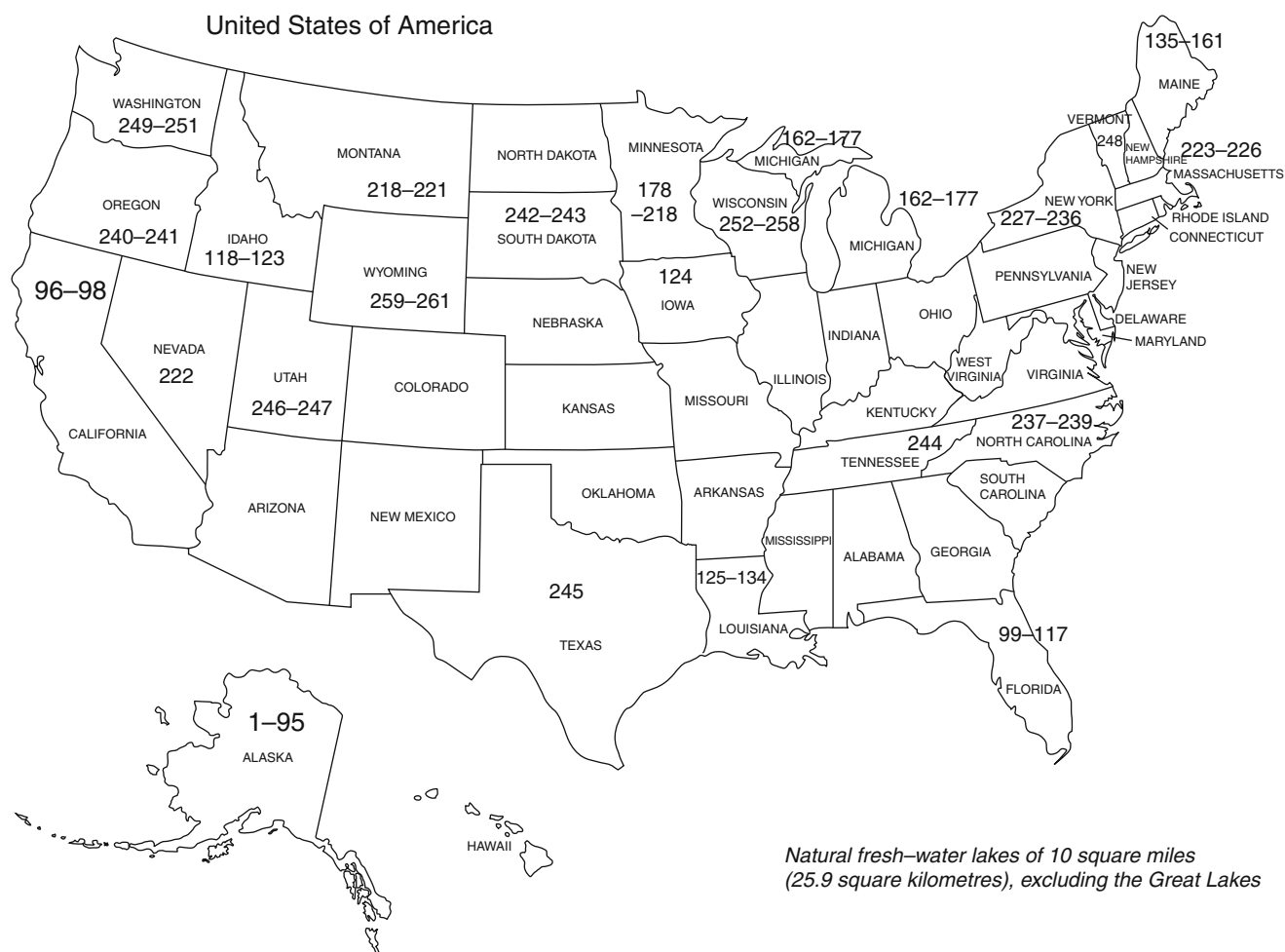
In view of the opportunity offered by lakes for the public good, a Lakes Study Commission was created to review anticipated recreational demand at lakes and developing recommendations for enhancing recreational use of these facilities.

United States: Principal Freshwater Lakes, Table 3 Principal saline lakes

Lake	Present area (sq miles)	Remarks
California		
Salton Sea Owens	350 dry at times each year since 1943	About 650 sq miles at highest stage in 1905–1907. 110 sq miles in 1872, prior to diversions from Owens River; 35 sq miles in 1943
Mono Goose (also in Oregon)	76 About 100	Maximum, 89 sq miles in 1919. Maximum, 186 sq miles, 125 in California and 61 in Oregon; overflowed into Pitt River in 1869 and 1881; dry in 1930; 150 sq miles in 1958
Eagle	41	Some questions as to whether Eagle Lake should be considered saline or freshwater. It has no surface outlet (Martin, 1962), but since 1924 it has been tapped by tunnel to Willow Creek. Salinity is considerably less 1,000 ppm, according to California Dept. of Water Resources. During period 1895–1925 lake rose to highest level since at least 1650 (Harding, 1935); rise believed due to closing of subterranean outlet by earthquake in 1890 (Antevs, 1938)
Honey	Dry	90 sq miles in 1867, possibly higher in 1890; dry in 1903; high in 1904; dry in 1924. Contained some water April 1958 to September 1960, and early in 1962
Louisiana		
Pontchartrain	625	These lakes are connected with the Gulf of Mexico, and are subject to tidal fluctuations
Sabine (Louisiana and Texas)	95	These lakes are connected with the Gulf of Mexico, and are subject to tidal fluctuations
Calcasieu	90	These lakes are connected with the Gulf of Mexico, and are subject to tidal fluctuations
Maurepas	90	These lakes are connected with the Gulf of Mexico, and are subject to tidal fluctuations
Salvador	70	These lakes are connected with the Gulf of Mexico, and are subject to tidal fluctuations
Nevada		
Pyramid	180	Maximum size, 220 sq miles. Low until 1860; reached extreme high level in 1862 and 1868 or 1869; nearly as high in 1890; began to drop in 1917 (Hardman and Venstrom, 1941)
Walker	107	Maximum size, 125 sq miles
Winnemucca	Dry	Maximum size, 180 sq miles. Dry in 1840, but began to fill shortly thereafter (Zones, 1961). According to Russell (1885), the lake rose more than 50 ft and approximately doubled its area between 1867 and 1882. Was 87 ft deep in 1882. Dry since 1945
Carson	Nearly dry	Maximum size, 41 sq miles. A few water-filled pot holes remain. Once called South Carson Lake; received flow of Carson River before Lahontan Reservoir was built
Carson Sink	Dry	A shallow playa some 250 sq miles in area shown on some maps as a body of water. Russell (1885) called it North Carson Lake. Dry in 1882, but probably has had some water at times since. Once received water from both Carson and Humboldt Rivers
Ruby		Maximum size, 37 sq miles. Shown as swamp on recent maps of Army Map Service and Nevada Dept. of Highways
Franklin		Maximum size, 32 sq miles. Shown as swamp on recent maps of the Army Map Service and Nevada Dept. of Highways
North Dakota		
Devils	24	140 sq miles in 1867; 70 sq miles in 1883; 45 sq miles in 1900; 10 sq miles in 1940. Since 1940 lake has been rising
Oregon		
Malheur and Harney	Probably dry	Malheur, the larger of the two lakes, overflows into Harney, which has no outlet. Maximum combined size, 125 sq miles. Reported dry in 1931; high in late 1950s; about 1 sq miles in 1961, and expected to go dry in 1962
Goose (see California)		
Abert	52	Maximum size, 60 sq miles. Dry in 1930 or thereabouts, but fairly high in 1958
Summer	Probably dry	Maximum size, 70 sq miles. Nearly dry in 1961

United States: Principal Freshwater Lakes, Table 3 (Continued)

Lake	Present area (sq miles)	Remarks
Silver	Dry	Maximum size, 15 sq miles. Dry in 1961. Because of the transient nature of the lake, the water – whenever there is any – is relatively fresh; hay is raised on the dry lake bed
Warner	Probably less than 10	A series of shallow lakes; combined area about 30 sq miles in 1953, a wet year, estimated from Army Map Service map based on aerial photographs taken in 1953. Present lakes are all that is left of Pleistocene Warner Lake, which covered about 300 sq miles and was about 270 ft deep
<i>Utah</i>		
Great Salt	About 1,000	Maximum size since 1851, 2,400 sq miles in 1870s; minimum, 950 sq miles in October 1961; seasonal high in 1962 was 1,050 sq miles in June
Sevier	Dry	Maximum size, 125 sq miles; has been dry for several years



United States: Principal Freshwater Lakes, Figure 1 The number of lakes in each state in numerical order from Table 1.

The following tables taken from the USGS Circular 476 (see Bue, 1963) is primarily a glossary of lakes in the United States that have a surface area of 10 sq miles (25.9 km²) or more.

Table 1 lists, by US states, the names and surface areas of lakes above 10 sq miles given by counties except those in Alaska where locations are given by latitude and longitude.

Table 2 includes lakes of 250 ft (76.25 m) or more in depth, although there may be deeper lakes in Alaska and elsewhere noted since the Circular was published in 1963.

Table 3 gives a list of the principal saline lakes.

Volume of lakes

The USGS estimate the volume of the lakes in Tables 1 and 2 from the equation:

$$\text{Volume} = \frac{1}{3} \text{maximum depth} \cdot \text{surface area}$$

In general, the equation gives results which are too low but satisfactory for making comparisons.

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Cross-references

[Great Lakes, North America](#)

[Water Balance of Lakes](#)

[Water Balance of the Laurentian Great Lakes](#)

URBAN LAKES AND PONDS

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Definition

An urban lake is an inland body of surface water surrounded by an urban environment and larger than a pond, while an urban pond is an inland body of surface water surrounded by an urban environment, but smaller than a lake.

A retention pond is a pond which has a permanent pool and is more or less vegetative. It treats storm water by removing pollutants from runoff through sedimentation, biological uptake, and plant filtration, but it also has a storage volume above the permanent pool that reduces runoff peaks caused by rain events. Synonyms to retention pond are wet pond, wet basin, or sediment pond.

A detention pond is a pond which only temporarily contains water, since it dries out between rain events. Its main purpose is to detain water and thereby reduce runoff peaks caused by rain events. Synonyms to detention pond are dry pond, dry basin, or detention basin.

History

The use of storage pools in gardens has been seen in cities at least since the establishment of the Old Kingdom in Egypt around 3000 BC. Public parks and gardens with water works were also widespread throughout the ancient Greek and Roman cities. In later times, urban lakes and ponds became more common in connection with rapid urbanization and the establishment of urban parks during the 1800s. The fundamental ideas behind this trend lay in the Romantic movement and the concept of public health. During the late 1700s, a reaction against the Enlightenment arose in Romanticism, which regarded nature as divine and a source of spiritual vitality for human beings. This was followed in the 1800s by the advent of many urban environmental problems related to industrialization – such as poor waste disposal and the pollution of air and drinking water. Thus, to improve people's health and give them fresh energy, urban parks and water environments were laid out (Plumptre, 1993; Benton and Short, 1999).

However, between 1975 and 1985 the view of these urban lakes and ponds changed. Now the issues were not only recreation and aesthetics, but also ecology and environmental technology. In the USA and Germany, numerous experiments were made to purify water with the help of ponds and wetlands. This contributed to the development of the subject of ecological engineering, as well as to a paradigm shift in landscape architecture and the introduction of the theory of sustainable landscape development (Campbell and Ogden, 1999). This new view was also promoted by the Rio Declaration of 1992, which emphasized an integration of economic, social, and ecological values. The result today is that urban ponds are an important component of sensitive or sustainable urban drainage. In stormwater management, urban ponds and lakes ideally provide, in addition to aesthetic values and greater possibilities for recreation, improvement of water quality and reduction of runoff peaks. The water in cities, including stormwater, is to be regarded as a resource and not a problem.

Essential concepts

There is no common consensus about what distinguishes ponds from lakes, but most often size is used as a criterion. There seems also to be a general idea that ponds may lie between 25 and 20,000 m² (Williams et al., 2003). An urban pond as well as an urban lake can receive water from streams and groundwater, and by direct urban runoff through pipes. The outflow may be natural in the form of a stream, or artificial by pipes. Most urban ponds and lakes are constructed, and are strongly affected by their urban surroundings as regards both water quality and hydrological load.

There is sometimes confusion about the difference between a pond and a wetland, even though this seldom leads to any problem. There are numerous definitions of a wetland, but also of how it differs from a pond. Two basic outlooks can be discerned. One considers a pond as a special case of a wetland. Then "wetland" becomes an umbrella term including ponds and shallow lakes. An example is the Ramsar Convention which uses a broad

definition of wetlands including everything from lakes, rivers, and estuaries to wet grasslands and peatlands. The other outlook is to consider the difference between wetlands and ponds as a matter of degree in the amount of permanent pool, i.e., vegetation. If the degree of permanent pool is 100% it is a pond, and if 0% it is regarded as a wetland. Noteworthy is that a “pool” in a garden context sometimes is interchangeable with “pond.” Here, a pool is always considered to be something constructed, and ideally with a fountain and a geometric form – circular, oval, or polygonal – whereas a pond often has a natural shape with waterside planting.

Urban lakes and ponds as examples of a multiple-use approach

Urban lakes and ponds have many functions that city planners, ecologists, landscape architects, and civil engineers try to combine in a multifunctional manner, so that social, biological, and technical values can be developed together.

Probably the most obvious aspect of social value is recreation. People can walk or jog along the waterside, have picnics, or just relax. If the water freezes during winter, skating is often very popular. In some lakes and larger ponds it is possible to fish or row and in some others, usually smaller ponds, stones are added for children to jump on; see [Figure 1](#). Urban lakes and ponds located in parks also add aesthetic values as well as improved microclimates during warmer weather. Then there may be educational values; e.g., school classes can visit to do nature studies (Campbell and Ogden, 1999). The popular Yamaguchi Park in Pamplona, Spain, has an urban pond shown in [Figure 2](#). This park, with its pond designed by Japanese landscape gardeners, also has a symbolic value since it constitutes a bond between the cities of Yamaguchi and Pamplona.

The characteristic of aquatic environments is that they are quickly colonized by organisms. This means that even small urban waters can acquire a high biodiversity. There are examples from Europe where red-listed species have been found after only a few years in newly built ponds. It is mainly insects that have the ability to fly as adults and colonize new environments, but also nonflying organisms such as flatworms and freshwater isopods will establish themselves quickly. However, in order for amphibians to benefit, the water must be fish-free and nearby land areas must be suitable. Good wildlife corridors will further support the establishment of new species and genetic exchange between populations. The most important wildlife corridor for aquatic organisms stretches along open watercourses. Building culverts in a watercourse is therefore detrimental to this spread. In addition, seeds and phyto- and zooplankton can hitchhike with birds when they visit the new ponds in search of food (Campbell and Ogden, 1999; Kadlec and Wallace, 2009).

Lakes, due to their size, have several advantages over ponds when it comes to reducing pollutant loads and flow peaks. Therefore, in stormwater management, an effort



Urban Lakes And Ponds, Figure 1 An example of a simple way to improve recreational value. Husie Mosse Malmö, Sweden. Photo Pekke Kärppä.

has been made to improve pond and wetland efficiency. The basic principles for pond design in terms of technical function, on the other hand, are contradictory. To improve the pollutant removal efficiency it is preferred to have as large a permanent pool as possible, whereas to detain water it is preferred that the stormwater pond has a large detention volume, i.e., it is better if the pond is empty when the rain begins. Normally, the outflow from a detention pond is designed to empty the pond within 1–2 days. To balance these two goals, an additional pond design has been developed that combines the detention and retention ponds – named an extended detention pond. Important factors that affect the sedimentation process and thereby also the pollutant removal capacity are



Urban Lakes And Ponds, Figure 2 Yamaguchi Park in Pamplona, Spain, illustrates an example of an urban pond.
Photo Jesper Person.

particle size, hydrological load, pollutant concentration, vegetation, pond surface area, and pond hydraulics, which, e.g., describe how water moves within a pond, effective volume, the amount of dead zones, and short-circuiting. It may be added that most of the pollutant removal occurs between rain events and not during an event (Mays, 2001; Persson and Wittgren, 2003).

Environmental problems

Urban lakes and ponds receive polluted water, since they are located within an urban environment with parks and paved surfaces. It is generally known that there are several pollutants which contribute to urban environmental problems, such as:

- Metals (such as lead, copper, cadmium, and zinc) and hydrocarbons such as oil and PAH that originate from traffic, which are all toxic and dangerous for fauna and vegetation as well as humans
- Sediment which increases turbidity and originates from eroding banks and road sanding
- Leakage from polluted soil, e.g., landfill and industrial areas
- Airborne pollutants such as sulfur and nitrogen that come with precipitation
- Chlorides from road salting
- Litter that degrades the beauty of surface waters and threatens wildlife
- Algae growth, which often occurs in ponds that are shallow and exposed to the sun, have little vegetation and low water circulation, and receive fertilizers

- Organic materials such as leaves and grass, which add to the load of oxygen-demanding material, and thereby reduce oxygen concentrations
- Herbicides and insecticides, which originate from management of urban green land such as parks, private gardens, playing fields, golf courses, and road verges

Current controversies

Today most people see stormwater ponds as sustainable water management and a good example of urban development. But there are also those who regard stormwater ponds as hazardous places since they expose humans and animals to polluted water, and not as adding ecological values (National Research Council, 2001). There are also those who highlight the risk that small children can drown, thereby creating a dispute not only about fens, but also about the existence of urban ponds per se. Another controversy is that there can be several problems connected with detention basins. That is, they may kill forests, destroy habitats for woodland species, or require permanent maintenance – and when they fail, they can actually create more damage than they were designed to prevent, such as flooding due to blocked outlets (Mays, 2001). It has also been found that a detention pond is little used by wildlife, in contrast to ponds with a permanent pool (Campbell and Ogden, 1999).

Summary

Urban lakes and ponds became ever more common when cities grew during the rise of industrialism. At first, their main purpose was to add aesthetic qualities in parks and

improve the health of city dwellers. Since the 1970s and 1980s, there has also been a vision that these systems can purify water and prevent flooding. In principle, lakes and ponds are distinguished by their size: a lake is larger than a pond, which has an area between 25 and 20,000 m². In park contexts, a pond is distinguished in turn from a pool: whereas a pond often has a natural shape with water-side planting, a pool often has a geometric form. Today, urban lakes and ponds are planned and developed so that they acquire multifunctional values. These range from social values such as recreation and aesthetics, or biological values such as diversity, to technological values like the fact that the systems can clean water and reduce flooding.

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Cross-references

[Artificial Wetlands](#)
[Lake Restoration](#)
[Reservoirs, Multipurpose Use of Small Reservoirs](#)

V

VENTING TURBIDITY CURRENTS IN RESERVOIRS

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Description

Turbidity currents are generally understood to stand for stratified flows in lakes or reservoirs caused by the differences in density of suspended sediment concentrations between the inflowing and the standing water.

Turbidity currents occur mainly during floods since high discharges and suspended sediment concentrations are often a consequence. What is significant about turbidity currents is the sudden submersion of the clear stagnant water by the turbid water, the plunge point. Subsequently, the turbidity currents layer at the bottom of a reservoir, continue moving toward the dam within the former streambed, and come to a halt when reaching the dam and transform in a so-called submerged muddy lake. The barrier of the dam causes the suspended material to settle, which is in many cases undesirably.

The probability of turbidity current events is a matter of correlation between hydrological and sedimentological predispositions, as well of the topography of a reservoir, e.g., its geometry, which is decisive for the tolerance of turbidity currents; since the reservoir has to be relatively short and straight with a substantial gradient, the valley should be V-shaped with steep slopes with the bottom outlet situated at a low level in the vicinity of the dam.

Fundamentally, such turbidity currents could be vented through a reservoir by opening low-lying gates like bottom outlets at precisely adjusted moments. The advantage of venting turbidity currents is in many cases the

desired reduction of sedimentation, the less frequent necessary variant of flushing, and the more ecological justifiable way to release sediments out of a reservoir.

According to respective literature, venting turbidity currents through reservoirs has been dealt with so far mainly in Asia, America, and Africa. Efficiencies between 50% and 80% have been documented concerning the prevention of inflowing sediment deposition, and that is very representative.

Not all reservoirs are suitable for supporting the venting of turbidity currents. This is predominantly a matter of whether turbidity currents occur at all along the reservoir bottom, and most importantly, whether they do not dissolve on their own after a certain distance. It is conceivable that turbidity currents mix with clear lake water along their way and reduce, therewith, their concentration differential, on one hand or on the other hand, it is also imaginable that they remobilize already-deposited fine material along their path and become, thus, consequentially stronger, heavier, and more accelerated. Knowledge about the flow situation, travel time between inlet and bottom outlet, as well as sediment concentrations, and temperature distributions in the reservoir are essential to assess the feasibility of venting.

Measurements of turbidity performed by the authors in a European Alpine reservoir showed that high sediment concentrations could be observed at the inlet of the bottom outlet during floods. It is recommendable, therefore, to open the bottom outlet in such a case, especially when the spillway is in operation, and thus potential water losses for the original purposes of the reservoir have not to be considered.

Acknowledgments

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currents on reservoir sedimentation – venting through a bottom outlet as an alternative (Contract Number 810977). Many thanks also to the economic partner and co-financer Verbund Hydro Power AG.

Cross-references

[Turbidity Currents in Reservoirs](#)

VICTORIA LAKE

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Introduction

Lake Victoria is the largest lake in Africa (68,800 km²), and the most important freshwater resource for the people living in its vicinity. The lake forms, together with Lake Kyoga and Lake Mobutu Sese Seko, an estimated reservoir of 3,200 km³ of freshwater. The sole outlet of Lake Victoria is the River Nile leaving the lake near Jina (Uganda), flowing through the Lakes Kyoga and Mobutu Sese Seko and contributing on average 14% of the flow in the combined White and Blue Niles as measured at Aswan. The flow of the Nile is relatively constant due to the natural regulatory effect of the three equatorial lakes.

Changes in the water balance of the lakes are of major importance not only to the riparian countries, but also to the countries north of these lakes, Sudan and Egypt, which receive water from the Upper Nile basin besides the Blue Nile from Ethiopia. In addition to increased damage to lake-shore interests in Kenya, Uganda, and Tanzania, large fluctuations in lake level result in variations in flow of the Nile which is of major importance to Egypt, a densely populated country totally dependent on the continued flow of its largest river for drinking water and for power generation. Significant jumps in flow of the river are related to higher water levels in Lakes Victoria and Mobutu. Increases in River Nile flows during 1960–1964 and 1977–1980 were clearly related to the rise in level in Lake Victoria in those periods. International agreements between Egypt and Uganda and between Egypt and Sudan were concluded as early as 1929. Regulation of the Nile has been a major issue since the early decades of this century to all the countries concerned. Water from the lake is used for irrigation purposes in all three countries.

Fisheries

Fishing and related post-harvest processing have been a very important economic activity in and around Lake Victoria, and a rapidly growing population of more than eight million people in its catchment area depends on the lake fisheries as a source of protein. After the introduction of gill nets in Lake Victoria in 1905, catches of the endemic fish species gradually declined due to increased fishing effort, as observed for the period 1905–1928.

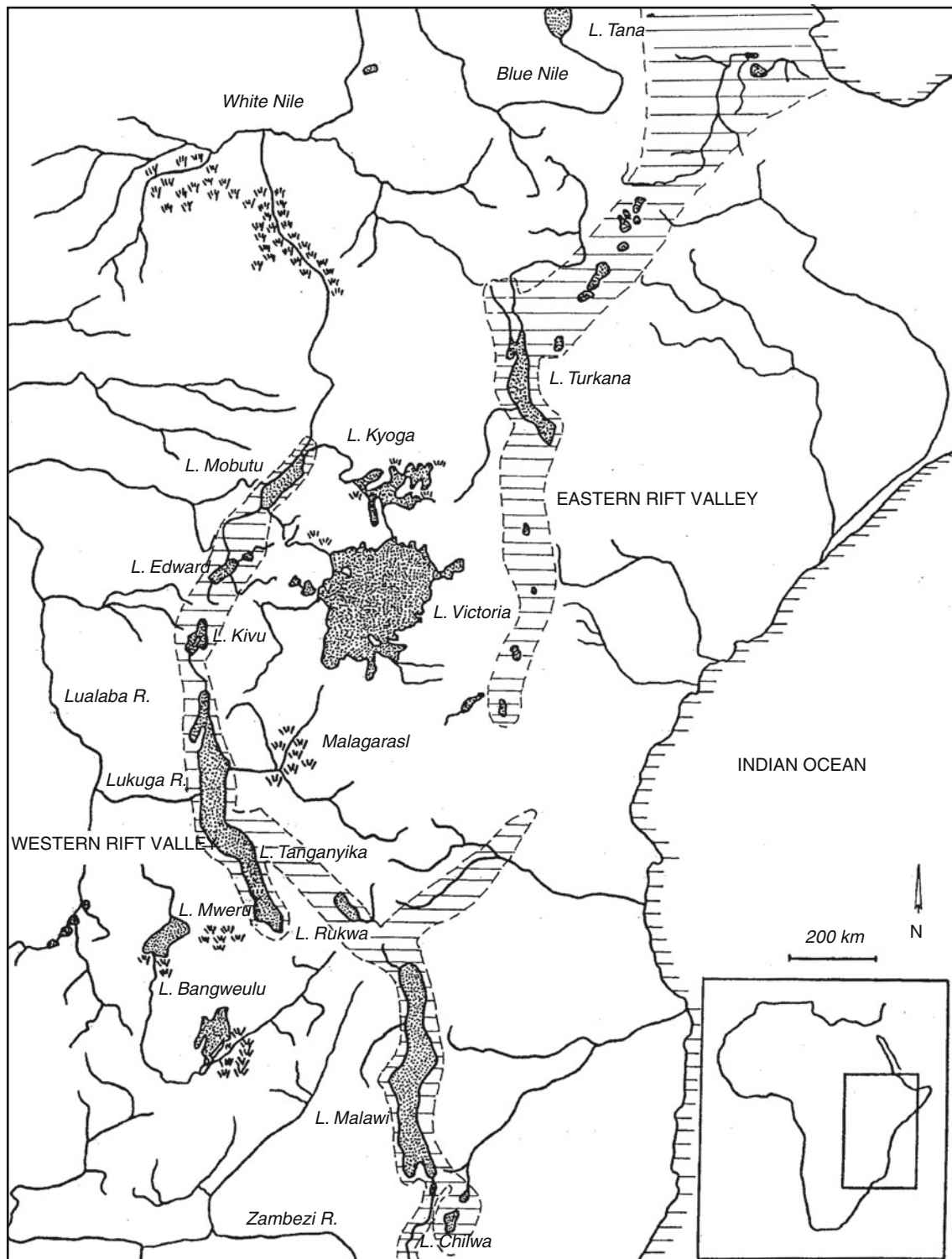
A further increase of fishing effort during the 1940s with the use of illegal undersized, mesh sizes and the introduction of nylon nets and outboard motors in the 1950s resulted in overfishing and a sharp reduction in the catches in the inshore areas.

The high demand for fish led to the introduction of exotic species into Lake Victoria. The tilapias *Oreochromis niloticus*, *O. leucostictus*, *Tilapia zillii*, and *T. remdalli* (“*melanopleaura*”) were introduced during the 1950s and 1960s and eventually replaced the indigenous species. The Nile perch found his way into the Lake in the early 1950s, by unofficial and official means, before the results of a pilot experiment carried out in Lake Kyoga in the 1950s to determine the advisability of stocking the Lake with fish were available. Recent research revealed that the Nile perch from Lake Victoria differs taxonomically from lake species collected elsewhere, including *L. niloticus rudolfianus*, *L. niloticus longispinus*, *L. albertianus*, *L. marcrophthalmus*, and *L. niloticus niloticus*.

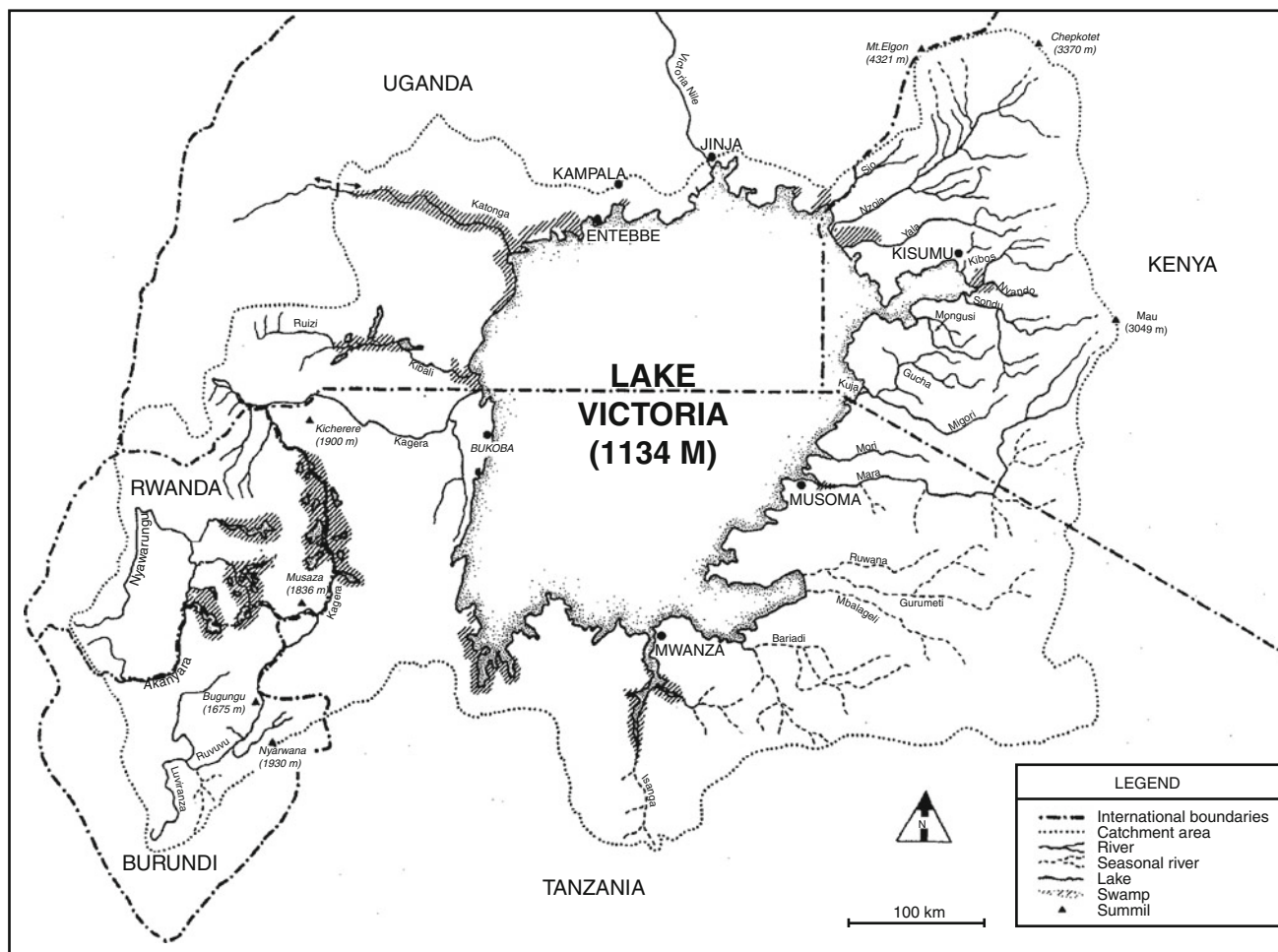
The introduced species resulted in increased commercial catches. In 1989, the lake produced over 500,000 t of fish, predominantly Nile perch (63%), dagaa (*Rastrineobola argentea*) (19%), and Nile tilapia (9%). Provisional estimates for the years 1990 and 1991, as official data are not yet available, would indicated that catches have been leveling off. The ecosystem is still largely unstable and the level at which the fish production of the lake will stabilize is simple not predictable. The management of the Nile perch fishery is therefore seen as an utmost priority. Predation by Nile perch and competition with introduced tilapias have caused a severe decline, and in some cases total disappearance, of native species.

Fish has always been an important source of food for people around the lake. The increased production of table fish from 44,000 to 405,000 t between 1975 and 1989 must have had a significant impact on the food availability around the lake basin and also to more distant urban centers in the three countries. The presence of Nile perch drastically changed the nature of fishing operations, fish processing, and marketing. The total value of production at market level has been estimated at US\$ 270 million for 1989. In Kenya and Tanzania the value of production increased by 500% and 750%, respectively, between 1985 and 1990 (Figures 1 and 2).

In August 1992, a Workshop on “People, Fisheries, Biodiversity and the Future of Lake Victoria” was held in Jinja. Summarizing current and recent research of limnology, ecology, and socioeconomics of the lake and its catchment in some 50 presentations, scientists from Uganda, Kenya, Tanzania, Europe, Israel, Canada, and the USA concluded that the limnology and environment of Lake Victoria are undergoing rapid change and that this will have serious implications for the fisheries of the Lake and result in a deterioration of the social and economic welfare of its riparian population. Resolutions in this workshop underscored the urgent need for understanding current changes in limnology of the lake and include



Victoria Lake, Figure 1 Eastern Africa showing the Rift Valleys and their lakes. Lake Victoria lies between the two rifts.



Victoria Lake, Figure 2 Topographic map of the catchment area of Lake Victoria.

the development of a general ecosystem model, the improvement of the understanding of the controls on oxygen distribution and levels of food web alterations, its effects on water quality and lake productivity, and the determination of the energy flows of the two major trophic detritus. Furthermore, it was recommended that research and management programmed for the fringing wetland and forest habitat should be undertaken and that special attention should be given to the explosive growth of the water hyacinth in the lake.

Research on the pollution of the lake and its catchment has become increasingly important in recent years. Pollution studies in Kenya have been carried out by the university of Nairobi and KMFRI. Recent hydrological research on Lake Victoria has mainly focused on the assessment of the different components of the water balance in order to predict changes in water level and the flow of the Nile.

Lake Victoria is a shared water body. Resources use by one of the riparian countries impacts the activities of the other countries. Regional cooperation in environmental

management of the lake basin is being envisaged with the assistance of UNEP and the World Bank in order to harmonize management objectives and to provide a framework within which to resolve user conflicts and transboundary issues.

Management of water availability, water quality, and lake pollution is only possible with an improved scientific understanding of the limnology and hydrology of the lake and of the effect of anthropogenic activities on the lake environment. This requires regional collaboration and coordination of limnological and hydrological research.

Emil Pasha, a German doctor, was a naturalist and ornithologist. During the 12-year stay on the Nile north of Jinja, he sent out thousands of birds and animals and thousands of specimen of plants of the region to museums in Europe. He also made records of rainfall and geology of the country. In 1890, on his way to his camp near Lake Albert, he founded the town of Bukoba on the western shore of Lake Victoria. Upon his return to the shore of Lake Albert he found his camp in total disorder. He went

on into the Congo, where he was killed in 1892 by a group of Arab slavers. He was the first pioneer naturalist combining the pure geographical exploration and scientific research in the fields of biology, geology, medicine, and anthropology. At this time, when most of the geographical problems had been solved, European scientists were becoming interested in the exciting new, virgin area of tropical Africa. The first scientific expeditions in the region were those of J.W. Gregory, a Scottish geologist who worked in the East African Rift Valley and J.E.S. Moore's expeditions to Lake Tanganyika in 1894 and 1897, which can be regarded as the foundation of tropical African limnology.

Hydrological research

Limnological investigations of Lake Victoria and other East African lakes evolved from rather short-term investigations in the beginning of the century mainly focused on collecting specimens and carrying out simple physical measurements, to more extended physical and chemical measurements, and finally to the foundation of research institutes on the shores of the lakes which permitted prolonged investigations and the use of research vessels.

Regular measurements of water level have been recorded since 1902 at Kisumu and the first bathymetric survey of the lake was completed in 1900. Stuhlmann, the zoologist who accompanied Emin Pasha on his trip to Lake Albert in 1890, was in 1892 the first collector of Algae from Lake Victoria at Bukoba and later several others followed.

Before the Second World War the first and only systematic biological research on Lake Victoria was the Fishing Survey of Lake Victoria in 1927–1928 by Micheal Graham. In appendix 3 of the report the physiography of Lake Victoria is described with information on geography, geology, the climate of the region, and some physical and chemical characteristics of the lake, and in Appendix 8 an outline of the ecology of Lake Victoria is given. Limnological observations on physical characteristics and a study on zooplankton of Lake Victoria were carried out during the Fishing Survey if 1927–1928 by Worthington.

After the Second World War newly founded research institutes and universities in the three territories around the lake (Uganda, Kenya, and Tanganyika) became increasingly important for hydrological and limnological research on the lake.

In 1947 the East African fisheries Research Organization (EAFRO) (later the East African Fresh Water Fisheries Research Organization) (EAFFRO) and presently the Uganda Freshwater Fisheries Research Institute (UFFRO) at Jinja (Uganda), was the first research organization established under the East Africa High commission and focused on Inland fisheries in East Africa. This organization, with R.S.A. Beauchamp as its first director, advanced to a large extent the knowledge of Lake Victoria and other East African inland waters and their fisheries. In 1975 substations of EAFFRO were established in

Kisumu (Kenya) and Mwanza (Tanzania). The station at Kisumu (Kenya) is now the Kisumu laboratory of the Kenya Marine and Fisheries Research institute (KMFRI). In Tanzania the substation first was renamed the Freshwater Fisheries Research Institute (FFRI). Presently it is a substation on the Tanzanian Fisheries Research Institute (TAFIRI).

In 1949 another organization was established under the East Africa High Commission with its headquarters in Kisumu (Kenya), the Lake Victoria Fisheries Service (LVFS). It became responsible for fishery production and management in the lake and had vessels based in Entebbe, Kisumu, and Mwanza.

The only major center for higher education at the time was Makerere College at Kampala, which was to become the first university in East Africa. Several departments of the university became involved in lake research. In Kenya, departments of the University of Nairobi, the second university in the region, were involved in hydrological and limnological research in the Kenyan waters of Lake Victoria, predominantly of the Nyanza Gulf. In Tanzania, the Tanzania fisheries Research Institute (TAFIRI) and departments of the third university in the region, the University of Dar-es-Salaam, have been responsible for limnological research on the lake. Finally, the Fisheries departments of the three countries, although mainly involved in fisheries, have carried out studies.

An important contribution to the limnology of Lake Victoria and African limnology in general has been made by the Freshwater Biological Association (FBA) of the UK, starting with R.S.A. Beauchamp the first director of EAFRO, who spent several years on the lake and the first director of the FBA, E.B. Worthington, who was already working on the lake in 1927. Past and present members of FBA have been engaged in limnological research on Lake Victoria. The Lake has been subject to several hydrological investigations of which the latest is the Hydromet Survey, a cooperative venture between the Nile Basin countries (Burundi, Egypt, Kenya, Rwanda, Sudan, Tanzania, Uganda, and Zaire with Ethiopia as observer), the United Nations Development Programme (UNDP), and the World Meteorological Organization (WMO).

Recent limnological research on Lake Victoria has been carried out by the local research institutes in cooperation with research institutes and universities in Europe and North America, and occasionally Japan, and international organizations such as FAO and UNESCO. Of all inshore waters, the bays near Jinja have the longest record of limnological research having been studied since the late 1940s when EAFRO was founded. Nyanza Gulf has been intensively studied during the last two decades. Research recently has been focused especially on the relations among fish kills, algal blooms, and eutrophication. Limnological studies in the Mwanza Gulf started in 1973 and were carried out continuously from 1978 by the HEST/TAFIRI project, although limnological monitoring was more or less limited to those parameters relevant to fish ecology and fisheries. The largest part of the lake, with offshore waters deeper than

60 m, was first studied in 1927–1928. Recently, limnological research on a number of offshore sampling stations, including underwater observations with operated vehicle (ROV), have been carried out as part of the eutrophication research projects in Uganda and Kenya.

Over the last 25 years a growing number of African limnologists have contributed to the limnology of Lake Victoria and other East African lakes, resulting in an increasing number of scientific publications on the subject.

History

The first scientific research on Lake Victoria goes back to the expeditions to find the sources of the Nile, which constituted the first hydrological research on Lake Victoria. A compelling book on the explorers and conquerors of the sources of the Nile was written by Moorehead and has been used as the main reference for the following short historical overview.

The European discovery of Lake Victoria was made by two German missionaries, Johann Krapf and Johann Rebmann, from a missionary post in Rabai near Mombasa. They were the first Europeans to see the mountains of Kilimanjaro (1848) and Kenya (1849), respectively. In 1855 they produced, together, with another missionary, J.J. Erhardt, a map showing a large inland lake called “Unyamwezi Sea.” At the same time there were local reports from Arab slave and ivory traders of two large lakes “Jimi” and “Nyanza” and a third lake “Nyasa” further south. The Royal Geographical Society in London became interested and supported an expedition by Richard Burton and John Hanning Speke to investigate the reports of the lakes and their relation to the River Nile.

They decided to start from Zanzibar and approached the lakes from the East African coast, and with this expedition the period of the Central African exploration began. In 1858 they first discovered “Ujiji,” the present Lake Tanganyika. During the expedition they heard about another lake further north and John Speke left Burton in Kazeh, now called Tabora (Tanzania), and reached the southeast end of the second large lake, which he named after Queen Victoria (the Gulf that he discovered was later named after him). In 1862 John Speke and James Grant found the outlet of Lake Victoria near Jinja. Later in 1875 Stanley circumnavigated Lake Victoria by canoe in two months (the first lakewide survey) and confirmed Speke’s hypothesis that it was one great lake with a single outlet at Ripon Falls (near Jinja). He started his trip near Mwanza, sailed directly to Ripon Falls along the east side of the lake, and returned along the west side to Mwanza. In the years following that trip other expeditions were made to or passed through the lake. In 1884 the Scottish explorer Joseph Thompson made a journey through Masailand and reached the northeastern shore of Lake Victoria east of Ripon Falls. In 1889 Stanley and Emin Pasha (Eduard Schnitzer) returned from the latter’s camp near Lake Albert along the southwest shore of Lake Victoria via Kazeh to Bagamoyo on the East African coast near Zanzibar.

With these explorers of the 1800s began the period of exploration of Central African lakes.

Appendix: Hydrology

Inflow 18.10^9 m^3
 Precipitation 100.10^9 m^3
 Outflow 23.10^9 m^3
 Evaporation 100.10^9 m^3
 Annual lake level fluctuations 0.4–0.7 m
 Maximum lake level fluctuation 3 m
 Flushing time 140 years
 Residence time 23 years
 Area $68,800 \text{ km}^2$
 Volume $3,200 \text{ km}^3$

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Cross-references

[Nile Basin, Lakes](#)
[Stratification and Mixing in Tropical African Lakes](#)
[Tanganyika Lake: Strong in Hydrodynamics, Diverse in Ecology](#)

VOLUME OF WATER IN LAKES AND RESERVOIRS: DETERMINATION

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Introduction

There are basically two methods of determining the volume, capacity, or storage of lakes and reservoirs:

1. Conventional surveying method
2. Electronic distance measurement (EDM) using the Global Positioning System (GPS) Total Station method

In both cases the objective is to establish a relation between water level and volume.

Volume determined by conventional surveying methods

This method, although now seldom used for the estimation of volume, requires a launch equipped with echo sounder, the position of the launch on the lake being fixed by sextant or theodolite. The soundings of depth are taken along carefully selected cross sections.

The positioning of the cross sections takes account of the size and shape of the lake or reservoir but is not usually more than 1 km apart, the general rule being that the volume between cross sections is representative of the volume of the valley between ranges. For best results, the selection of cross sections is similar to that in the selection of verticals in streamflow measurement so that the volumes of each segment (the volume between cross sections) should not be more than a specified percentage of the total volume. Targets, in accordance with ISO 4366, are located at both ends of each section to maintain the launch on the section line.

Contours are plotted using all measured values of soundings on the cross sections, both below and above the water surface. The scale of the plot depends on the size and area of the lake or reservoir and may be to a scale of between 1:200 and 1:20,000 with a vertical scale of about 20–30 cm (see Figures 1 and 2 and Table 1).

The total volume is estimated by the use of the prismoidal end area or other method using the area enclosed by each contour with a constant vertical interval between each contour.

If staff or reference water level gauges are available, these are read at suitable intervals during the survey.

As stated above, the method is seldom used today especially if the surface area of the lake or reservoir is

greater than, say, 500 km² and whose linear dimensions are more than 10 km. It should be noted, however, that Sir John Murray's bathymetric survey of 562 Scottish lochs during the period 1897–1909 used this method albeit using equipment only available at that time.

Bathymetric maps

For example, a bathymetric map can be generated by appropriate software in conjunction with EDM or GPS equipment. See Figures 1 and 2 and Table 1.

Volume estimated by modern surveying methods

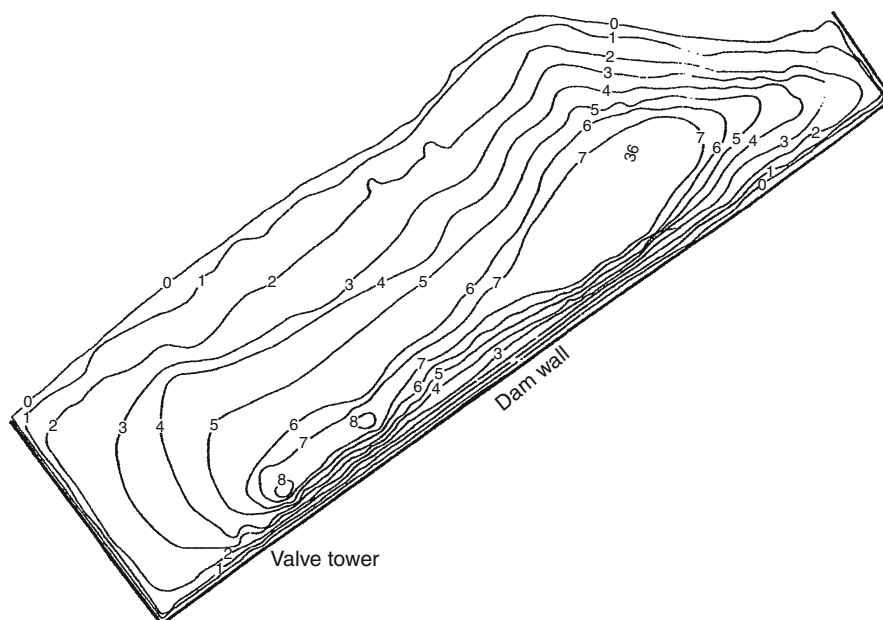
The introduction of a fully integrated survey system uses a combination of theodolite, EDM instrumentation, data processor, and dedicated software giving x, y, and z coordinates directly and encompassing everything from field observations to the production of the final plans. The system is known as the Total Station.

All survey data are transferred from the Total Station to an electronic notepad allowing input in three-dimensional coordinates.

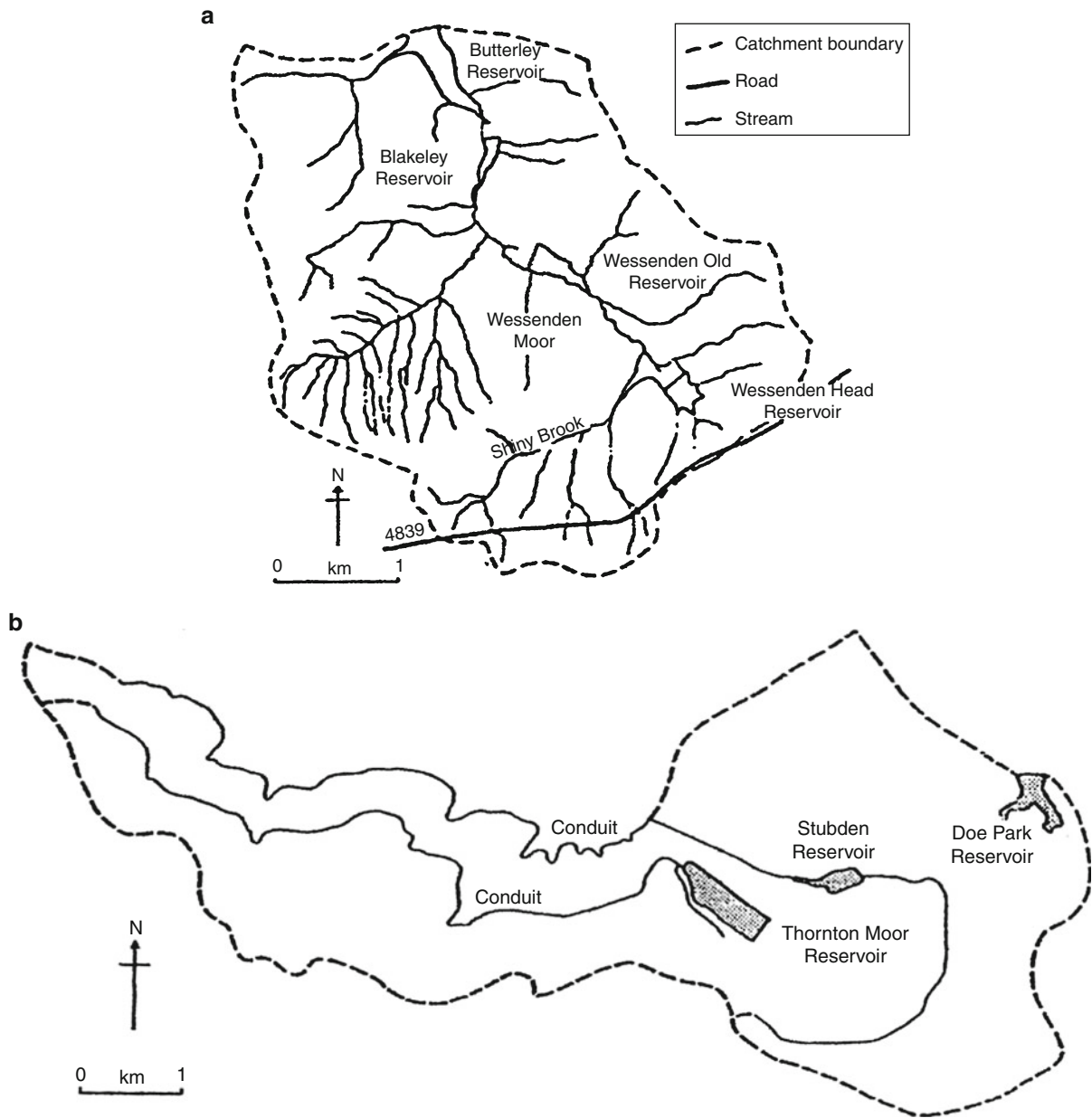
The system, apart from speed and accuracy, allows the largest of lakes and reservoirs to be surveyed, the maximum range of an EDM Total Station being about 8 km.

The system is based on measuring the transit time of an electromagnetic beam emitted from a transmitter-receiver to a reflecting target and back.

A combination of EDM and theodolite allows the electromagnetic beam to pass through the telescope optical system. The prisms are carefully located round the lake or reservoir with respect to the EDM Total Station and the launch position. These modern techniques no longer require the tedium of working along cross sections.



Volume of Water in Lakes and Reservoirs: Determination, Figure 1 Bathymetric map of Thornton Moor Reservoir, UK.



Volume of Water in Lakes and Reservoirs: Determination, Figure 2 Location of study areas. (a) Wessenden Head and Blakeley Reservoirs (b) Thornton Moor, Stubden and Doe Park Reservoirs.

Volume of Water in Lakes and Reservoirs: Determination, Table 1 Loss of reservoir capacity

Reservoir parameter	Wessenden head	Wessenden old	Blakeley	Butterfly	Thornton moor	Stubden
Date of construction	1881	1835	1903	1907	1885	1868
Catchment area (km ²)	← 15.05 →				5.12	1.94
Original capacity (MI)	373	486	364	1,832	795	451
Revised capacity (MI)	358	321	137	1,724	702	406
Loss of capacity per century (%)	3.7	23	75.2	7.5	11.3	8.2
Annual loss of capacity (m ³)	137	1,220	2,736	1,365	895	318
Annual area-specific loss (m ³ /km ² /year)	← 362.66 →					

The GPS receiver

Twenty-four GPS satellites (see "Appendix") orbit the earth twice per day at an altitude of 20,200 km. Receivers on the ground calculate their positions by making distance measurements to four or more satellites. These satellites function as reference points which broadcast satellite identity, position, and time information by a carrier frequency of 1575.42 MHz in the UHF band. Measurements of distance to each individual satellite are made by analyzing the time taken for a signal to travel from a satellite to a GPS receiver. Trilateration is then used to establish the GPS receiver's position, and since latitude and longitude and height of each point are displayed, distances between points are also displayed.

The GPS system of surveying

A receiver on the launch displays position and sounder data. With such a receiver in the traveling mode, the GPS Total Station can troll the lake or reservoir without the necessity of defining range locations. One base station set up can serve many roving unit outstations equipped with receivers and data links within a 10-km radius. There is, therefore, no practical limit to the size of the lake or reservoir to be surveyed; it only depends on the number of base stations and rovers which can be set up.

The survey can be extended by mounting the GPS Total Station on a vehicle and provide contour and topographic information. For small water bodies, a combination of vehicles and surveyors with backpacks can be employed. Each GPS receiver, whether tripod mounted, vehicle mounted, rover, or backpack, accepts and processes raw distance signals from multiple GPS satellites. All GPS data and sonar data are transferred directly from handheld survey controllers and converted by dedicated commercially available software packages into the necessary output of bathymetric maps, contour plans, lake or reservoir configuration, three-dimensional drawings, and water level volume curves.

The rover unit merges carrier phase data broadcast from the base station with incoming satellite signals to establish three-dimensional coordinates of the survey points with an accuracy of 10 mm.

Water level measurement

The water level is measured according to ISO 4373. The number of water level measuring stations depends on the size and shape of the lake or reservoir. The objective is to ensure that the measured values are sufficient to establish the mean horizontal water level and the volume of live, total, or flood storage.

To determine the number of stations necessary, consideration is given to any wind setup, surface curvature, outflows and inflows, seiches, and long-wavelength waves.

The following table is given as a guide (Table 2):

Volume of Water in Lakes and Reservoirs: Determination, Table 2 Guide to determine the number of necessary stations

Surface area km ²	10,000	5,000	1,000	500	<500
Number of water level stations	6–8	4–6	2–4	2	1

For small reservoirs (<500 km²), the location of a reference or staff gauge at the draw-off tower is common practice especially if a relation can be established between the gauge and average water level.

Acknowledgement

Acknowledgement is made to the International Standards Organization, Geneva, for permission to reproduce Figures 1 and 2 and Table 1 at www.iso.org.

Appendix

The GPS satellite system

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of 24 satellites placed into orbit by the US Department of Defense. GPS was originally intended for military application, but in the 1980s the U.S. government made the system available for civilian use. The GPS works in any weather conditions anywhere in the world 24 h a day. There are no subscription fees or setup charges.

The GPS satellites circle the earth twice a day in a precise orbit and transmit signal information to earth. GPS receivers take this information and use triangulation to calculate the user's exact position.

Essentially, the GPS receiver compares the time a signal was transmitted by a satellite with the time it was received. The time difference tells the GPS receiver how far away the satellite is. With distance measurements from a few more satellites, the receiver can determine the user's position and display it on the unit's electronic map.

A GPS receiver must be locked on to the signal of at least three satellites to calculate a 2D position (latitude and longitude) and track movement. With four or more satellites in view, the receiver can determine the user's 3D position (latitude, longitude, and altitude). Once the user's position has been determined, the GPS unit can calculate other information such as speed, bearing, track, trip distance, distance to destination, sunrise and sunset time, etc.

The GPS receivers are extremely accurate and three to five meters are common.

The 24 satellites that make up the GPS space segment are orbiting the earth about 12,000 miles (19,000 km) above the earth making two complete orbits in less than 24 h. The satellites travel at speeds of 7,000 miles/h (11,000 km/h). They are powered by solar energy having backup batteries onboard to keep them running in the event of a solar eclipse when there is no solar power. Small rocket boosters on each satellite keep it orbiting in the correct path.

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Cross-references

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 Reservoir Capacity
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VÕRTSJÄRV LAKE IN ESTONIA

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Synonyms

Estonian name: Võrtsjärv; English name: Lake Võrtsjärv;
 Russian name: Озеро Вуртсъярв
 Historical name forms: Werzjerw See; Wirtsjerw See; See Wirzjerw; Озеро Вирцерв

Location and catchment geography

Lake Võrtsjärv, the second largest lake in the Baltic countries, is located in a shallow preglacial basin in the southern part of Estonia, centered around 58°17'N and 26°03'E (Figure 1). At mean water level, the lake area is 270 km², volume 750 millions m³, mean depth 2.8 m, and maximum depth 6 m. The deep site located close to the eastern shore in the southern part of the lake is confined to a small area where sediment accumulation is prevented by strong compensating currents occurring at most wind directions (Kivimaa et al., 1998). The meridionally oriented axial length of the lake is 34.8 km and the maximum width 13.3 km. The coasts are generally low except at the eastern side where Devonian sandstones are exposed in places as steep banks. There are 4–5 small moraine islands in the southern part of the lake.

From the 3,374-km² drainage basin (including the lake itself), 3,275 km² is located in Estonia and 99 km² in Latvia. The basin is conventionally bordered by the 40-m isohypse, while the altitude of the lake surface is 33.63 m at the long-term mean water level. Major part of the drainage basin (53%) is covered by forest, agricultural lands make up 33%, water bodies 9% (mainly the lake itself), and wetlands 3% of its total area (Figure 2). The outflowing Emajõgi River connects the drainage basin to the watershed of Lake Peipsi (47,800 km²). Among the 154 rivers and streams within the Võrtsjärv catchment, only 40 have a length over 10 km. The longest is the Õhne River (94 km) and the largest the Väike Emajõgi River, which basin occupies 40.9% of the total catchment area (Figure 1).

Since 2006, the whole lake and parts of its shore ecosystems are included in Võrtsjärv limited conservation area, which largely overlaps with the Võrtsjärv Site of Community Importance and Võrtsjärv Special Protection Area under Natura 2000.

Geology of the lake basin and bottom deposits

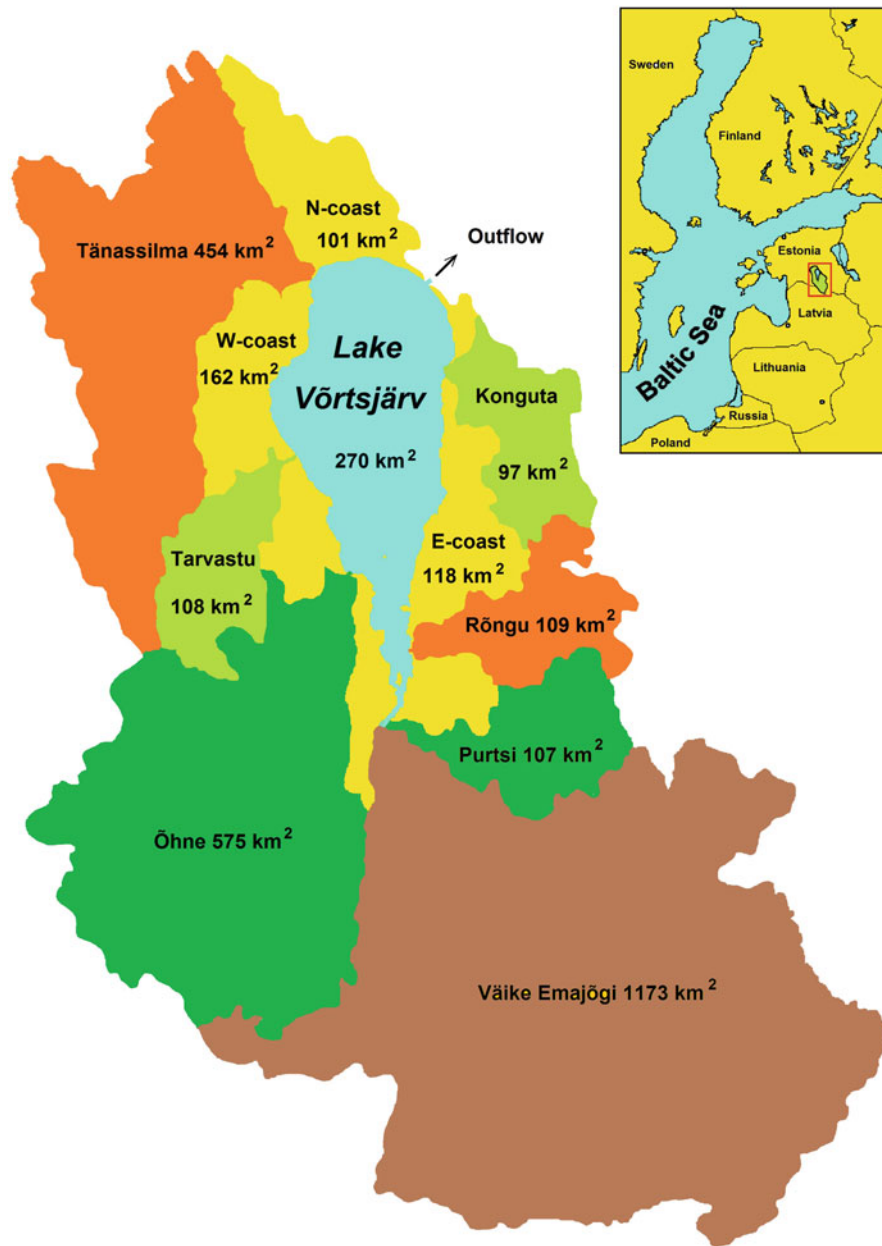
The Võrtsjärv depression in the Middle Devonian baserock is of preglacial origin but has been strongly influenced by deglaciation processes and tectonic movements. According to Moora and Raukas (2004), after the retreat of the ice from southern Estonia began some 13,000 ¹⁴C years ago, first, a narrow fluvial body of water, so-called Small Võrtsjärv, formed that developed into a larger Ice Võrtsjärv, which water level was controlled by the Peipsi ice-dammed lake. The stage of the Ancient Võrtsjärv started from the final lowering of the water level and development of an outflow into the Baltic Ice Lake around 12,000 years ago. The beginning of the Holocene marks the boundary between Ancient Võrtsjärv and Big Võrtsjärv, a transgressive body of water of considerably larger area than the present lake. The stage of Contemporary Võrtsjärv started when the outflow to the west finally closed and the outflow to the east via the Emajõgi Valley opened some 7,500 years ago, lowering the lake level. Presently, due to an uneven neotectonic land uplift, Lake Võrtsjärv is retreating southward, inundating new areas (Miidel et al., 2004).

Varved clays accumulated in Ice Võrtsjärv and sand and silt in Ancient Võrtsjärv (Moora et al., 2002). Lake marl accumulation started in the Big Võrtsjärv stage in the Early Holocene (Miidel et al., 2004). Biogenic sedimentation, coastal erosion, and transport of suspended solids by rivers are the principal sources of material for the bottom deposits of Võrtsjärv. About two thirds of the lake bottom is covered with mud lying on marl, and the thickness of these layers increases toward the south reaching 7 and 4.7 m, respectively (Veber, 1973). Varved clays lying under marl are exposed in the form of a sandy, muddy-sandy, or clayey bottom, mostly in the northern part of the lake.

Hydrology

According to the annual mean water balance of the lake for the period 1961–2000 (Järvet, 2004), 83% of the lake's water income was accounted for by the inflow from rivers and 17% by direct precipitation on the lake surface. The water losses partitioned in nearly similar proportions (84% and 16%, correspondingly) between the outflow and evaporation. The components of the balance have a clear seasonal dynamics with the highest income during the spring flood peak and the highest outflow and evaporation during summer (Figure 3). The average water retention time is one year. During higher water periods, on average 16 days per year, reverse flow may occur in the upper course of the River Emajõgi, leaving the lake without outflow (Järvet, 2004).

The long-term (1922–2003) mean water level of Võrtsjärv is 33.63 m above sea level. In September 1996, the water level dropped to 32.20 m, the lowest value ever recorded in Võrtsjärv, and the highest water level (35.28 m) was measured in November 1923 (Järvet, 2004).

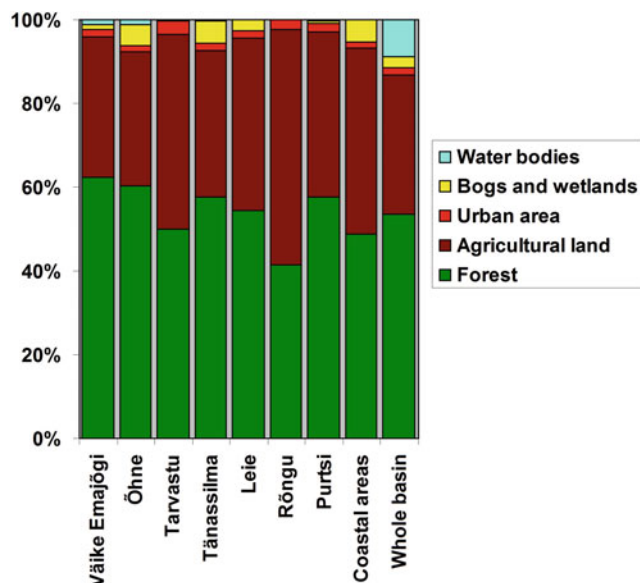


Võrtsjärv Lake in Estonia, Figure 1 Location map of Võrtsjärv and the main sub-basins of the catchment. (Modified from Järvet et al. 2004.)

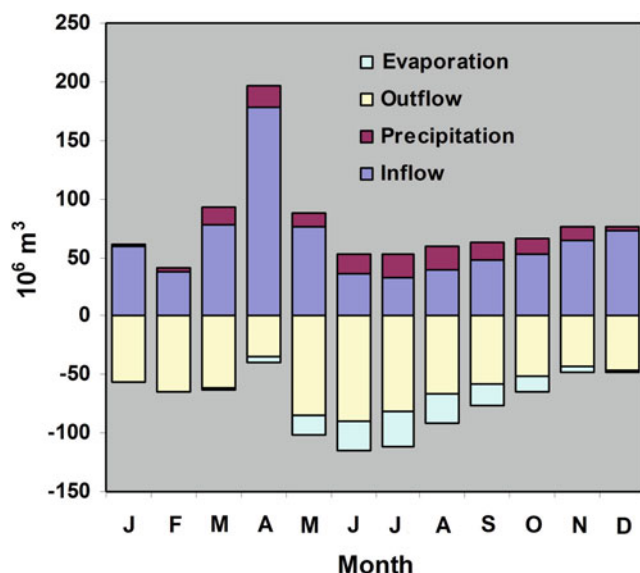
The absolute water level range of 3.1 m exceeds the mean depth of the lake and corresponds to a 1.4-fold (89 km^2) difference in the lake area, 2.4-fold (2.2 m) difference in the mean depth, and 3.3-fold ($845 \times 10^6 \text{ m}^3$) difference in the lake volume (Table 1). Large seasonal and annual fluctuations of the water level are one of the most characteristic features of Võrtsjärv. Because of the restricted outflow, it takes the entire summer for the flood water to leave the lake, whereas the height of the flood peak in spring strongly determines the annual mean water levels

($R^2 = 0.85$, $p < 0.0001$, Järvet, 2004). The annual mean amplitude of the water level is 1.4 m.

Nearly coincident periodicities in annual water levels and the North Atlantic Oscillation index for winter (NAOw) can be found for several large lakes in north-eastern Europe (Figure 4). In Võrtsjärv, NAOw was negatively correlated with the end of the ice cover and positively with the lake's mean depth in spring. The influence of NAOw on water levels is likely achieved through the variable amount of precipitation (Nõges et al., 2010a).



Vörtsjärv Lake in Estonia, Figure 2 Catchment land use based on data published by Järvet and Nõges (1998).

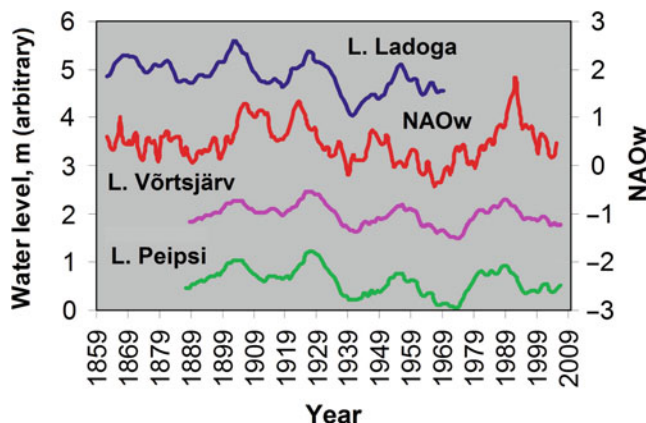


Vörtsjärv Lake in Estonia, Figure 3 Mean monthly water balance of Lake Vörtsjärv for the period from 1961 to 2000. The loss components of the balance are marked as *negative*. (Data from Järvet 2004.)

Vörtsjärv is polymictic. Water temperature reaches its maximum usually in the second half of July or at the beginning of August. The annual maximum surface water temperature has varied from 20.4°C to 27.5°C with a long-term average of 23°C for the period 1947–2000 (Järvet, 2004). Based on daily data for the ice-free periods of 1961–2004, there has been a highly significant

Vörtsjärv Lake in Estonia, Table 1 Water level characteristics in Vörtsjärv (Based on data from Järvet 2004)

Water level, m a.s.l.	Date, period	Mean depth, m	Area, km ²	Volume, 10 ⁶ m ³
35.28 – abs. maximum	26.11.1923	3.71	327	1,214
33.63 – long term average	1922–2003	2.79	270	750
32.20 – abs. minimum	06.09.1996	1.55	238	369



Vörtsjärv Lake in Estonia, Figure 4 Spatial coherence in annual mean water level of three large lakes in north-eastern Europe. Water level data for Lake Vörtsjärv (Estonia) and Lake Peipsi (Estonia/Russia) were obtained from the Estonian Institute for Meteorology and Hydrology (Data for Lake Ladoga (Russia) were taken from Jaani (1973). All series were smoothed with a 7-year moving average. The time series of the North Atlantic Oscillation index (Hurrell et al., 2001) is shown for comparison).

($p < 0.01$) temperature increase of 0.42°C per decade in August (Nõges, 2009).

The annual ice cover lasts on average for 131 days (minimum 55, maximum 168 days in 1923–2003) from mid-November until mid-April (Järvet, 2004). The maximum ice thickness has varied from 26 to 98 cm with a mean value of 52 cm.

Underwater light conditions

The diffuse attenuation coefficient $K_{d,PAR}$ ranges typically from 1.54 to 2.95 m⁻¹ in Vörtsjärv, resulting in 5–20-fold attenuation of photosynthetically active radiation (PAR) by one meter layer of water. The euphotic depth, estimated as the penetration depth of 1% of the subsurface PAR, varies from 1.6 to 3.2 m, most covering the 2.8-m water column. In Vörtsjärv, pure water absorbs 7–11% of PAR, phytoplankton pigments 11–20%, and scattering accounts for 19–25%, while humic substances may absorb 40–52% of total PAR. From January to March, snow cover causes 40–60% of the losses of incident light, while the

light attenuation by ice varies from 4% in December to about 26% in March (Reinart and Nõges, 2004).

Water and sediment chemistry

Waters collected by the tributaries from the surrounding moraine uplands have an alkalinity around 200 mg l^{-1} (Table 2) and are dominated by hydrocarbonate and calcium ions. The alkalinity and conductivity of water are highest in winter and decrease by about 20% in summer due to phytoplankton activity. The water is well buffered, and the mean pH ranges from 7.9 in winter to 8.5 in summer. The state monitoring data (1994–2009) show significant upward trends in alkalinity for spring and summer and in pH for summer, autumn, and winter. A rapid increase in sulfate and chloride concentrations from the 1950s to the 1980s was followed by a decrease in the following decades. The continuous decrease in the chloride concentration from 18 in 1989 to 7 mg l^{-1} in 2001 is the most striking change among the major ions. The most probable reason for this is the disintegration of large collective farms and the construction of wastewater treatment facilities (Tuvikene et al., 2004). Suspended solids concentration has a remarkable seasonal variation due to strong sediment resuspension and abundant phytoplankton during the ice-free period.

Võrtsjärv is highly eutrophic, characterized by mean annual total nitrogen (TN) concentration of 1.4 mg l^{-1} and total phosphorus (TP) concentration of $50 \text{ } \mu\text{g l}^{-1}$ (Table 2).

The riverine nutrient loading into Võrtsjärv increased rapidly in the 1980s followed by a decrease in the early 1990s caused by declining agricultural land use intensity in Estonia (Liira et al., 2008). For the period 1992–2007, TP concentrations in the main inflow of Võrtsjärv showed a highly significant decreasing trend (Nõges et al., 2010a)

reflected also in total loadings (Figure 5). TN loadings, which declined rapidly during the 1990, have slightly gone up again in the 2000s, whereas the drop in TP loadings continued.

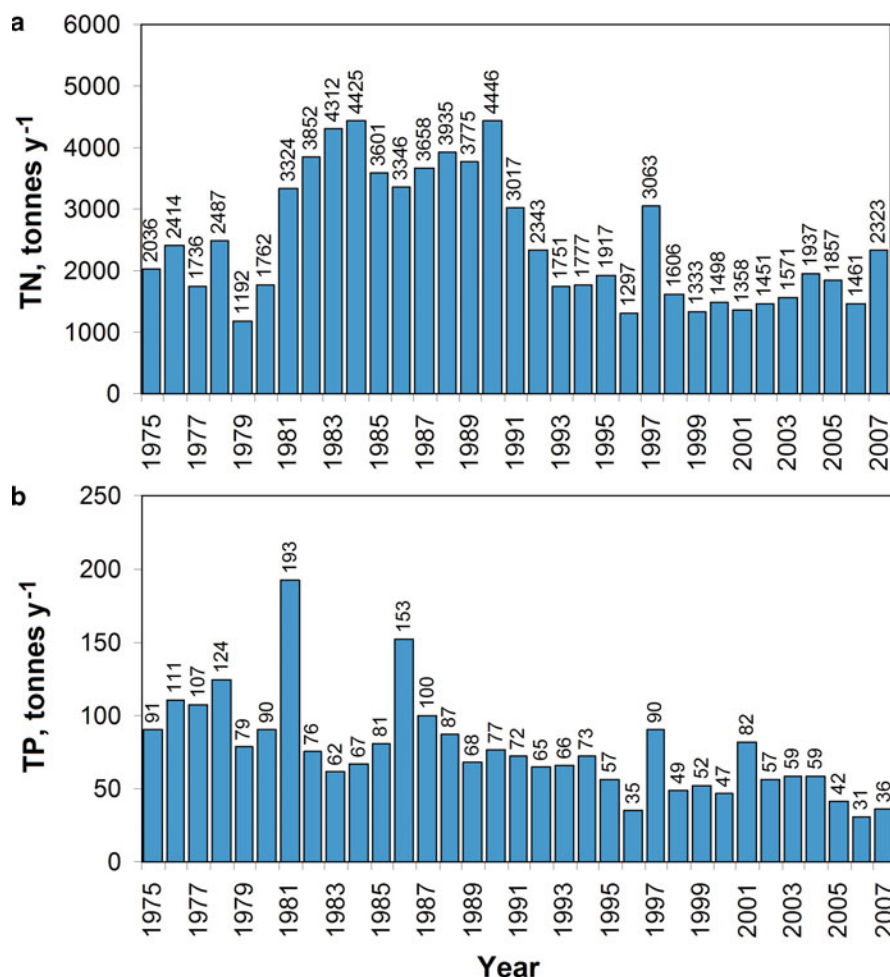
The state monitoring data (1994–2009) revealed significant ($p < 0.05$) decreasing trends in in-lake TP concentrations for spring and summer with corresponding rates of -0.7 and $-1.8 \text{ mg m}^{-3} \text{ year}^{-1}$, and in nitrate nitrogen concentration for summer. The strongest trends among the analyzed chemical variables were found in permanganate oxygen demand (COD_{Mn}), which increased with a rate of $0.26\text{--}0.32 \text{ mg O l}^{-1} \text{ year}^{-1}$ for all seasons. As biochemical oxygen demand was rather decreasing, the change in COD_{Mn} can likely be attributed to an increase in the concentration of humic substances. Dissolved oxygen concentrations increased highly significantly for winter over the 16-year period, obviously due to more frequent mild winters in the later years. Secchi depth declined highly significantly for winter and summer, which could be caused by the increase in both humic substances and chlorophyll *a* (Chl-*a*) concentrations.

Erosion bottoms with predominantly coarse materials, such as sand and gravelly sand, predominate in the northern part of the lake. Southward, a smooth transition over silty sand, sandy silt, silt, silty clay, and sapropelic silty clay to gyttja (Raukas, 1995) marks the trajectory of sediment focusing in the lake. Wind and wave action accounts for 87% of the observed spatial variability of sediment dry weight in Võrtsjärv (Nõges and Kisand, 1999b).

In the upper 0–2-cm sediment surface layer, sediment dry weight (DW) remains mostly below 10% of the wet weight (WW) but may reach as high as 60% in the erosion area. The organic matter content is around 20% of DW, on average, but varies from less than 5% of DW to more than 35%. Accumulation of lighter sediments to more sheltered

Võrtsjärv Lake in Estonia, Table 2 Seasonal statistics of main physical and chemical variables in Võrtsjärv based on monthly monitoring data from 1994–2009. The year was split into 3-month seasons starting winter from December

Variable, unit	Winter		Spring		Summer		Autumn		Year		Median	25th %tile	75th %tile
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev			
Dissolved oxygen, mg l^{-1}	11.6	3.4	10.8	2.9	9.5	1.4	11.5	1.8	10.8	2.6	10.9	9.3	12.6
Secchi depth, m	1.3	0.5	1.3	0.5	0.8	0.2	0.7	0.2	1.0	0.5	0.9	0.7	1.2
pH	7.9	0.2	8.1	0.4	8.5	0.3	8.3	0.2	8.2	0.4	8.2	7.9	8.5
Alkalinity, mg l^{-1}	228	40	196	43	181	21	198	22	201	37	195	180	219
Ammonium nitrogen, mg l^{-1}	0.21	0.13	0.14	0.15	0.03	0.03	0.04	0.07	0.11	0.13	0.05	0.02	0.17
Nitrate nitrogen, mg l^{-1}	0.93	0.55	0.95	0.60	0.07	0.08	0.12	0.12	0.54	0.60	0.30	0.05	0.90
Total nitrogen, mg l^{-1}	1.72	0.51	1.73	0.63	0.96	0.24	1.16	0.34	1.41	0.57	1.30	1.00	1.70
Phosphate phosphorus, mg m^{-3}	16	14	13	10	11	8	15	18	14	13	10	5	20
Total phosphorus, mg m^{-3}	42	17	44	16	53	22	60	37	50	25	45	35	59
Dissolved silicon, mg l^{-1}	3.2	1.0	2.2	1.3	1.0	0.8	2.1	1.3	2.2	1.4	2.0	1.0	3.3
Conductivity, $\mu\text{S cm}^{-1}$	398	65	343	69	316	24	335	25	348	59	336	317	367
Suspended solids, mg l^{-1}	6.4	5.9	10.2	9.1	20.4	10.6	22.4	17.1	14.7	13.2	13.0	5.0	20.0
Biochemical oxygen demand, mg O l^{-1}	2.3	0.9	3.1	1.4	4.9	1.3	4.6	1.3	3.7	1.7	3.7	2.3	4.9
Permanganate oxygen demand, mg O l^{-1}	12.5	2.9	11.9	3.1	13.1	2.0	13.3	2.3	12.7	2.7	12.4	11.0	14.0



Võrtsjärv Lake in Estonia, Figure 5 Long-term dynamics of nitrogen (a) and phosphorus loading (b) to Võrtsjärv.

bottom areas is reflected also in the horizontal distribution of sediment phosphorus forms which correlate strongly (R^2 from 0.72 to 0.96) with the dry matter content of the surficial sediment (Nõges and Kisand, 1999b). Phosphate release from the sediment is usually prevented by high Fe/P ratio (26:30) and the aeration of the sediment surface by frequent resuspension, that keeps phosphate adsorbed and maintains a low concentration of soluble reactive phosphorus in pore water (typically $<10 \mu\text{g l}^{-1}$). At low water levels, however, severe storms can entrain substantial quantities of the deeper, anoxic sediments, releasing occasionally large amounts of phosphorus (Nõges and Kisand, 1999a).

Budgets of substances

Võrtsjärv acts as an efficient trap for nutrients, which accumulates more than a half of the external N load and about one third of the external P load during the annual cycle. The nitrogen loss is mostly accounted for by denitrification while phosphorus is buried in the sediment. Seasonal and inter-annual variations in the water level have a major effect

on the annual nutrient budget of the lake. A comparison drawn between 2 years, 1990 and 1995 (Nõges et al., 1998), showed clearly how the retention of nutrients was regulated by the combined effects of rainfall and water level fluctuations. In low-water years, the external P loading to the lake is smaller; however, resuspension becomes stronger and more phosphorus is released from the sediment. Also, the loading of TN is smaller in low-water years, but unlike phosphorus, nitrogen losses are strongly enhanced by resuspension that brings nitrates into contact with anoxic sediment layers, the site for denitrification. As a result, most of nitrogen is released to the atmosphere.

Examination of a 28-year record found that both water color and COD_{Mn} were positively related to discharge throughout the year, with significant correlations in the months of March and June and from August to November (Nõges et al., 2007). In addition, water color and COD_{Mn} in spring were positively related to the NAOw index of the previous winter, reflecting the occurrence of increased precipitation in high NAO years. A recent study (Pall et al., 2011) showed that the lake retained nutrients

(N, P, and Si) irrespective of whether the water retention was positive or negative, but the balance between accumulation and emission of total organic carbon (TOC) and dissolved inorganic (DIC) and organic carbon (DOC) depended strictly on lake's water budget.

Biota

Phytoplankton

Primary production (PP) of phytoplankton in Võrtsjärv has been measured in situ with ^{14}C -assimilation technique in 18 years during the period from 1982 to 2009. The full time series was reconstructed, using a semi-empirical PP simulation model (Arst et al., 2008) based on continuously measured PAR irradiance and interpolated values of monthly measured Chl-a. According to the long-term annual PP ($208 \pm 27 \text{ gC m}^{-2} \text{ year}^{-1}$), Võrtsjärv is close to the global nutrient-saturated production boundary for lakes determined by latitude where light limitation has the leading role (Nöges et al., 2011). This assignment is supported by the composition of phytoplankton dominated by eutrophic and highly shade tolerant cyanobacteria from the genus *Limnothrix*.

Although more than 500 taxa of algae have been identified in phytoplankton, phytobenthos, and periphyton of Võrtsjärv (Pork and Kõvask, 1973), the phytoplankton of the lake can be considered species-poor, and usually, two to three species form the bulk of the biomass. Cyanobacteria and diatoms dominate overwhelmingly, while all other groups of algae together commonly build up less than 10% of the biomass. Among these minority groups, chlorophytes, cryptophytes, dinophytes, and chrysophytes are more abundant, whereas euglenophytes and xanthophytes are rare.

Among cyanobacteria, two filamentous species, *Limnothrix planktonica* (Wolosz.) Meffert and *L. redekei* (van Goor) Meffert, are the most numerous, occurring in plankton all year round. These species are accompanied by two other filamentous cyanobacteria, *Planktolyngbya limnetica* (Lemm.) Kom.-Legn. and *Aphanizomenon skujae* Kom.-Legn. & Cronb. The diatoms are dominated by long cylindrical *Aulacoseira* species and needle-shaped species of *Synedra*. Because of strong wave action, benthic and periphytic diatoms from genera *Surirella*, *Gyrosigma*, *Nitzschia*, and others become detached from the substrate and occur frequently in phytoplankton. Only in spring, spherical, ellipsoidal, or disk-shaped algae from different taxonomic groups may become temporarily dominating. A study carried out in Võrtsjärv from August to December 1997 showed the important role of autotrophic picoplankton ($<3 \mu\text{m}$), which formed on average 14% of the total phytoplankton biomass and contributed 30–70% to the total PP for this period (Nöges et al., 2004).

Seasonally, the control of phytoplankton growth is mediated by ice conditions in spring and by water level in summer and autumn (Nöges et al., 2010a). Large year-to-year differences in the water level have a pronounced effect on the development of the phytoplankton.

Since 1964, the phytoplankton biomass has been significantly lower in years of high water level, a pattern that was not related to any change in external loading of nutrients (Nöges et al., 2010b). Besides the largely variable nutrient loadings, fluctuating water levels have had a particular role in the succession of dominating species. A study of the 44-year data series on Võrtsjärv phytoplankton (Nöges et al., 2010c) suggests a non-linear response of phytoplankton to changing nutrient loadings and the occurrence of a regime shift between 1977 and 1979 triggered by an abrupt water level increase, which supported the establishment of the new highly shade tolerant phytoplankton community dominated by *Limnothrix redekei* and *L. planktonica*. Low-water periods are often characterized by an increase in the nitrogen-fixing species, *Aphanizomenon skujae*. Nitrogen fixation, recurrently measured in Võrtsjärv in summers with low water levels, has likely been triggered by increased nitrogen losses due to denitrification (Tönno and Nöges, 2003).

Macrophytes

Despite its shallowness, Võrtsjärv is not a macrophyte-dominated lake, and the area colonized by macrophytes is less than 25% of the total lake area (Table 4). A large diversity of habitats supports a great variety of different species including, besides real aquatic plants, several species of wetland and swamp vegetation. Over time, a total number of 114 species have been described in the lake (Mäemets, 2002).

The littoral zone of Võrtsjärv has a very gentle slope. The average width of an up to 1 m deep zone is 250 m, varying from 50 to 700 m. The littoral zone is covered by a wide belt of aquatic macrophytes, dominated by *Phragmites australis* (Cavan) Trin. ex Steud. (common reed) and some other helophytes such as *Schoenoplectus lacustris* L. Palla (common club rush) and *Typha angustifolia* L. (narrow leaf cattail), and is frequently bordered by the nymphaeid *Nuphar lutea* L. Sm. (yellow water lily) (Feldmann and Nöges, 2007). The stands of helophytic vegetation are quite dense, the average number of stems ranging from 14 to 23 m^{-2} for reed, 30–37 m^{-2} for club rush, and 13–14 m^{-2} for cattail (Liira et al., 2010).

The macrophyte vegetation of the lake has a strongly polarized character. The wind-exposed northern and eastern coasts are bordered by a species-poor, partly fragmentary reed belt, while the southern corner of the lake is fully overgrown with vegetation. In this part of the lake, all vegetation zones are abundantly represented. The vegetation along the more wind-protected western coast is richer compared to the eastern coast and has a denser and wider helophyte zone bordered in places by *N. lutea* and a continuous belt of well-established submerged vegetation. The polarized character of macrophyte distribution in the lake resulting from the particular combination of the dominating wind direction, the shape of the lake basin, and the irregular distribution of the inflows (Feldmann and Nöges, 2007) were noticed already by the Baltic German botanist Klinge (1890) who formulated his rule on

the impact of dominating wind direction on overgrowing of lakes.

A retrospective analysis of satellite images (Liira et al., 2010) for the period 1985–2007 showed that the helophytic macrophyte belt, dominated by *P. australis*, has rapidly widened during the last two decades, with an average expansion rate of 2.2 m year^{-1} , which was amplified 1.6 times the vicinity of large inflows. Expansion of reeds and decline of several submerged and shallow-water species in response to eutrophication are typical changes observed as well in Lake Peipsi, the largest lake in the Baltic states (Mäemets, 2002).

According to ^{14}C measurements in the littoral area in summer, the dominant submerged macrophytes, *Potamogeton perfoliatus* L. and *Myriophyllum spicatum* L., contributed 58%, their epiphytes 0.1%, and littoral phytoplankton 41.9% of the $12.0 \text{ g C m}^{-2} \text{ day}^{-1}$ total PP of the submerged macrophyte area. The littoral area contributed 35.5% to the total PP of the lake in summer (Nõges et al., 2010b).

Bacterioplankton

In 1963–2001, the total number of bacteria varied from 0.28–11 (average 3.7) mln cells ml^{-1} , reaching a maximum in the mid 1970s and a minimum in the mid 1990s (Tammert and Kisand, 2004), and has been increasing since then (Estonian State Monitoring, 2011). The bacterial biomass (BB) is low under the ice ($<75 \text{ mg C m}^{-3}$) and varies during the rest of the season from 100 to 500 mg C m^{-3} with the highest values from July to September. Bacterial production (BP) is generally low from November to February ($<150 \text{ mg C m}^{-2} \text{ day}^{-1}$) and high ($300\text{--}700 \text{ mg C m}^{-2} \text{ day}^{-1}$) from June to September. The BP/PP ratio is very low during the spring diatom bloom, while after the collapse of cyanobacteria in late summer to autumn, the BP/PP typically increases (Tammert and Kisand, 2004).

Genetic (PCR-DGGE of partial 16 S rDNA sequences) and functional fingerprints (CLPP by BIOLOG GN microplates) of the bacterioplankton enabled the identification of 36 different operational taxonomic units (OTUs) (Kisand and Nõges, 2004). The lowest numbers of OTUs (up to 10) occurred in July and the highest (up to 21) in November. Highly productive bacterial community preferentially utilized simple carbohydrates, whereas amino acids and organic acids involved in amino acid metabolism were preferably utilized during transition periods between winter and early spring, and late summer/early autumn when BP was relatively low but BB was high.

Zooplankton

A total of 307 zooplankton taxa have been identified in Võrtsjärv including 172 rotifers, (Rotifera), 47 cladocerans (Cladocera), 14 copepods (Copepoda), 73 ciliates (Ciliata), and 1 mollusc – *Dreissena polymorpha* juv.

Ciliates are studied in Võrtsjärv since 1995. There are 73 ciliate taxa found in Võrtsjärv with the greatest species

diversity occurring in June (Zingel and Nõges, 2010). Oligotrichs (the most common genera *Rimostrombidium*, *Limnostrombidium*, *Pelagostrombidium*, and *Halteria* and species *Codonella cratera* and *Tintinnidium fluviatile*) are the most numerous group (27–78%), being followed by prostomatids (11–25%), haptorids (4–34%), scuticociliates (0.3–22%), and peritrichs, the latter present only during warm seasons and never found in winter. The other ciliate orders found are Colpodida, Nassulida, Heterotrichida, Hymenostomatida, Hypotrichida, Pleutostomatida, and Suctorida. The biomass of ciliates is accounting for more than 60% of the total zooplankton (meta- and protozooplankton) biomass. Seasonally, the abundance of ciliates is highly variable (Table 3). Maximum ciliate abundance (285 cells ml^{-1}) and biomass ($15.4 \mu\text{g ml}^{-1}$) were found in August 2006 and the respective minimum values in February 1995 (0.8 cells ml^{-1} and $0.02 \mu\text{g ml}^{-1}$). Ciliate abundance peaks in spring (May) and reaches its maximum in late summer (July, August). Large-sized nanovorous oligotrichs dominate in spring. The summer peak is made up of small scuticociliates and oligotrichs, feeding mainly on picoplankton. The highest biomass values are not always coupled with the peak abundances, but with the occurrence of large ($>300 \mu\text{m}$) gymnostomes. A positive correlation between ciliates and phyto- and bacterioplankton shows that ciliate community is food-controlled. As both bacteria and phytoplankton are coupled with resuspension of lake sediments, the largely fluctuating water level influences the annual abundance of the ciliate community.

A total of 234 metazooplankton taxa belonging to planktonic and planktobenthic forms have been found in Võrtsjärv. The dominating species by number ($>20\%$ of total number) are the rotifers *Anuraeopsis fissa* (Gosse), *Keratella cochlearis* (Gosse), *Keratella quadrata frenzeli* (Eckst.), *Trichocerca rousseleti* (Voigt), *Polyarthra luminosa* Kut., *Polyarthra dolichoptera* Idels., and *Synchaeta verrucosa* Nipk., the latter two in winter. The biomass dominants ($>20\%$ of total biomass) are the cladocerans *Bosmina c. coregoni* Baird, *Bosmina longirostris* (Müller), *Chydorus sphaericus* (Müller), and *Daphnia cucullata* Sars, and the copepod species of genus *Mesocyclops*. All dominants are characteristic of eutrophic lakes. The number of simultaneously dominating species is small, and the functioning load is divided unevenly between species.

During 1994–2009, the mean metazooplankton biomass varied by season from 0.1 in winter to 1.7 g m^{-3} in summer, being on average 0.8 g m^{-3} (Table 3). The biomass of predatory zooplankton formed on average 18% of the total zooplankton biomass. The abundance is rather high while the biomass is low because of the large share of small-bodied rotifers to the whole zooplankton community. The mean individual weight is very small in Võrtsjärv, fluctuating between 0.7 and $3.2 \mu\text{g}$ with a mean value of $2.5 \mu\text{g}$ for the vegetation period (Haberman and Virro, 2004). According to the same authors, zooplankton production is low due to poor food conditions, with mean values

Võrtsjärv Lake in Estonia, Table 3 Seasonal statistics of main plankton variables in Võrtsjärv based on monthly monitoring data from 1994 to 2009. The year was split into 3-month seasons starting winter from December

Variable, unit	Winter		Spring		Summer		Autumn		Year		Median	25th %tile	75th %tile
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev			
Chlorophyll a, mg m ⁻³	14.5	15.4	18.6	14.2	38.7	13.6	55.6	20.5	31.4	22.9	29.7	12.3	45.5
Phytoplankton biomass, g m ⁻¹	4.5	5.3	6.5	6.4	21.1	11.2	27.2	14.4	14.5	13.8	11.5	2.7	22.0
% of cyanobacteria in biomass	63	30	34	26	72	18	79	12	62	28	71	43	83
% of diatoms in biomass	15	22	41	27	21	14	17	11	24	22	18	8	32
Ciliate number, thous. l ⁻¹	8.1	16.6	50.7	47.7	98.4	70.7	42.4	28.9	51.3	56.5	32.5	6.3	72.2
Ciliate biomass, g m ⁻³	0.4	1.5	1.8	2.0	3	3	1.6	2.4	1.8	2.6	0.8	0.13	2.3
Metazooplankton number, ind. l ⁻¹	117	126	602	925	1087	1,171	328	471	535	862	210	69	609
Metazooplankton biomass, g m ⁻³	0.1	0.1	0.5	0.7	1.7	1.6	0.7	0.7	0.8	1.1	0.3	0.08	1.1
% of copepods in total number	2.9	9.8	10.1	15.5	21	13	10.4	12.5	11.2	14.4	4.8	0.00	17.3
% of cladocerans in total number	2.0	4.9	1.8	3.5	24	24	34.6	28.5	15.8	23.8	3.1	0.00	21.3
% of rotifers in total number	95.0	10.9	87.8	16.7	55	31	54.9	30.7	72.9	30.2	84.6	53.35	98.5
% of copepods in biomass	8.7	22.9	20.8	23.8	34	18	18.6	19.5	20.6	23.0	13.5	0.00	31.4
% of cladocerans in biomass	7.9	16.1	7.8	14.3	52	22	57.2	26.6	31.6	31.0	23.4	0.00	58.6
% of rotifers in biomass	83.4	28.3	70.2	28.3	13	14	24.1	25.1	47.4	38.4	37.9	8.82	93.5
Total number of bacteria, millions ml ⁻¹	1.6	1.3	1.9	1.5	4	2	2.8	1.9	2.5	1.9	1.8	1.09	3.4

Võrtsjärv Lake in Estonia, Table 4 Colonization of Võrtsjärv by aquatic macrophytes in 2006–2009 (T. Feldmann, unpublished)

Life form	Colonized area, km ²	Percentage of lake area
Emergent plants	11.26	4.17
Floating-leaved plants	3.49	1.29
Submerged plants	47.83	17.72
Total	62.6	23.2

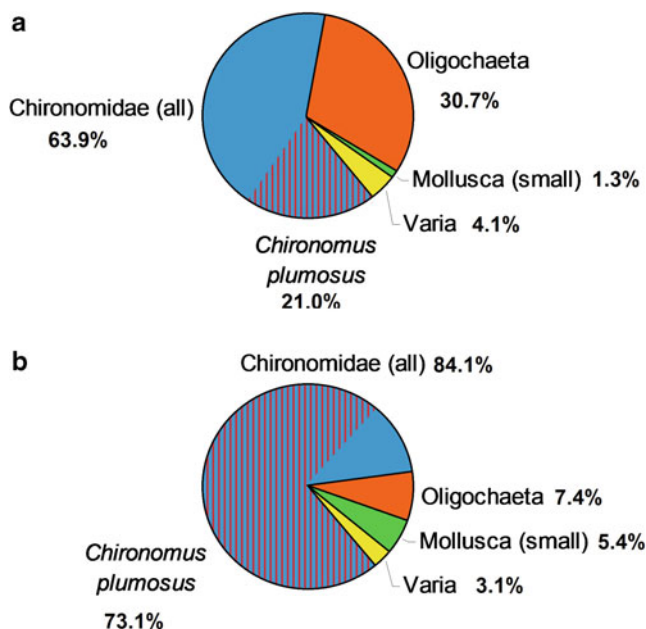
ranging for herbivorous zooplankton from 0.03 to 1.6 g C m⁻² month⁻¹ and for predatory zooplankton from 0 to 0.2 g C m⁻² month⁻¹.

During the last 40 years, the zooplankton biomass has not undergone great changes, but the species composition has been reflecting the changes in the lake's trophic state. The species characteristic of oligo-mesotrophic waters have totally disappeared or their abundance is declining (Haberman and Virro, 2004). Among zooplankton groups, the share of copepods in zooplankton biomass has significantly increased in summer, autumn, and winter for the period 1995–2009, while the share of rotifers has decreased in winter. By numbers, the share of rotifers has increased in summer on the account of decreasing share of cladocerans.

Zoobenthos

The weighted average abundance ($\pm$ standard error) of the zoobenthos without large molluscs over all habitat zones was 804 ± 56 ind m⁻² and the wet biomass 6.48 ± 0.88 g m⁻² in 1973–2003 (Kangur et al., 2004). The weighting factors were based on the areal proportions of the main types of benthic habitats, considering that 15%

of the lake bottom area is accounted for by the shallow vegetated littoral, 22% by the vegetation-free hard bottom sublittoral deeper than 1 m, and the remaining 63% is the profundal with a bare mud bottom at depths larger than 1 m. Chironomidae and Oligochaeta with a few dominating species make up the bulk of zoobenthos in the lake. Larvae of Chironomidae, with about 150 larval forms identified in the lake, represent the most diverse, widely distributed, and abundant group, accounting for more than 60% of the total zoobenthos abundance and more than 80% of the biomass (Figure 6). The most important species, *Chironomus plumosus* L. constitutes 73% of the average zoobenthos biomass (up to 90% in some years), and its relative importance has been increasing in the course of eutrophication. This species has either one or two generations in Võrtsjärv. The sublittoral chironomid fauna is somewhat richer, but most chironomid taxa in Võrtsjärv are limited to different littoral habitats with specific communities found on sand, stones, and muddy sand or mud among the macrovegetation. The distribution of chironomid assemblages in Võrtsjärv has not changed much during recent decades. The Oligochaeta are notably surpassed by the Chironomidae in abundance. A total of 54 species of Oligochaeta have been recorded from the lake, most of them from the littoral. *Potamothenix hammoniensis* (Michaelsen) is almost the single oligochaete species in the profundal, forming about half of their individuals in the open region. On muddy sand bottom, *Psammoryctides barbatus* (Grube) and *Limnodrilus hoffmeisteri* Claparède are common, often accompanied by *Potamothenix hammoniensis*. The two former species prevail also in the littoral. Seventy species of the Mollusca have been recorded from Võrtsjärv including 34 species of Gastropoda and 36 of Bivalvia. Among gastropods, *Valvata piscinalis* (Müller)



Võrtsjärv Lake in Estonia, Figure 6 Percentages of main groups of bottom animals (without large Mollusca) by abundance (a) and biomass (b) in Võrtsjärv in 1973–2003. (Based on data from Kangur et al., 2004.)

is the most common. The large unionid clams *Unio tumidus* Philipsson and *Anodonta anatina* (L.) are common everywhere in the sublittoral and the littoral. The abundance of *Dreissena polymorpha* Pallas an invader first found in Võrtsjärv in the 1950s, gradually declined to a few single individuals found by the turn of the century. The average biomass of the large molluscs, 1.6 g m^{-2} in the whole lake, is four times less than the total biomass of all “small” benthic animals but four times more than that of the small molluscs.

The main reasons for seasonal fluctuations in the amount of Võrtsjärv zoobenthos are the emergence of chironomids and other aquatic insects in summer, and fish predation. Large annual fluctuations with average abundance ranging from 401 to $1,601 \text{ ind. m}^{-2}$ and biomass from 1.6 to 26.4 g m^{-2} in different years are determined mostly by the variability of *Chironomus plumosus* in the profundal, which revealed a clear 3–4-year periodicity. A general increasing trend in the biomass of Chironomidae and Oligochaeta and decreasing trend in Mollusca and other groups were noticeable until 1996 (Kangur et al., 1998); however, the amount of zoobenthos decreased again in Võrtsjärv during the late 1990s.

Fishes and fisheries

Currently, 31 fish species and one lamprey species inhabit Võrtsjärv and its tributaries permanently. Rainbow trout and carp, escaped from fish ponds, have been caught occasionally but do not spawn in the lake. Four species, pike (*Esox lucius* L.), eel (*Anguilla anguilla* (L.)), bream

(*Abramis brama* (L.)), and pikeperch (*Sander lucioperca* (L.)), are presently the main very abundant commercial fishes. Also, the second-rate commercial fishes, such as roach (*Rutilus rutilus* (L.)), burbot (*Lota lota* (L.)), and perch (*Perca fluviatilis* L.), with annual catches ranging between 2 and 20 tons, are abundant or very abundant. During the last 2–3 decades, ruffe (*Gymnocephalus cernuus* (L.)), bleak (*Alburnus alburnus* (L.)), and lake smelt (*Osmerus eperlanus* m. *spirinchus* Pallas) have become abundant or very abundant as well, but they have lost their commercial importance as the use of fine-meshed trawls is prohibited in the lake since the 1970s. The remaining 24 species are non-abundant or rare with no or very limited commercial importance. Asp (*Aspius aspius* (L.)) and wels (*Silurus glanis* L.) are fully protected all the year round (Järvalt et al., 2004).

The abundance of pike in Võrtsjärv depends mostly on water level in spring. At high water levels, the floodplains, which are the favorite spawning areas for pike, are extensively flooded. Large pike catches in Võrtsjärv follow periods of high water level, as a rule, with a 4–5-year lag, whereas a similar lag separates small catches from periods of low water level.

The construction of the Narva hydropower station in the early 1950s blocked the natural route of eel from the Baltic Sea to the lake. As a result, eel almost disappeared from the lake's fish fauna. At present, owing to the 43 million elvers and 2 million young eels introduced since 1956, eel has become the most important commercial fish in the lake, turning Võrtsjärv the main site of eel production in Estonia. The biggest annual catches of eel in Võrtsjärv have exceeded 100 t.

Bream is the most productive commercial fish in Võrtsjärv. Since 1974, all catch limitation on bream was lifted because it began competing seriously for food (first of all, *Chironomus plumosus* larvae) with the far more valuable eel. The unlimited catch had even a positive effect on bream through improved feeding conditions: its growth rate accelerated, and it became fleshier and tastier. Unlike pike, bream can successfully spawn also during low-water periods in the lake (Järvalt and Pihu, 2002). Võrtsjärv has now acquired several characteristics of a bream lake. It is not impossible that it will become a pikeperch–bream lake in the future.

Spawning of pikeperch in Võrtsjärv is favored by low water, which warms up sooner, enabling earlier spawning and extends the growing period of the fry (Järvalt and Pihu, 2002).

Ruffe as the most important consumer of zoobenthos in Võrtsjärv and the main food competitor for eel and bream is regarded as the most unwanted fish species in the lake.

In case low water level and a severe winter coincide, serious fish kills may occur in the lake. Fishery has reached an optimum level in Võrtsjärv. The profitability of fishery in Võrtsjärv depends mainly on the condition of the stocks of pikeperch, pike, and eel. Large predators control the number of rough small fish, while eel accounts for the bulk of the income from fishery.

Food web functioning

The transformation of energy fixed by primary producers within the food web of Võrtsjärv is ineffective (Figure 7). The production of herbivorous zooplankton and benthic macroinvertebrates is 40 times lower than the PP of phytoplankton. The efficiency of the predatory links is much higher. The production of predatory zooplankton constitutes more than 10% of the production of herbivorous zooplankton, while the production of non-piscivorous fish makes up 12% of the production of its food objects (zooplankton, benthic invertebrates), and the production of piscivorous fish forms 13% of the production of non-piscivorous fish. It is evident that the low efficiency of the food chains in Võrtsjärv is the result of the large number of links at the beginning of the chain. Most of the organic matter produced by phytoplankton is not consumed by herbivores but enters the pool of detritus and is consumed in detrital food chains represented by the microbial loop and benthic animals. This is reflected by the high production of bacteria (70% of primary production) and the extremely abundant ciliate community. In Võrtsjärv, microbial loop prevails in the food web, and ciliates have a major role in it (Kisand and Zingel, 2000). The most abundant ciliate species in Võrtsjärv are euplanktonic pico- and nanovores, which are well adapted to the shallow and highly turbid ecosystem. Grazing studies (Zingel et al., 2007) showed that

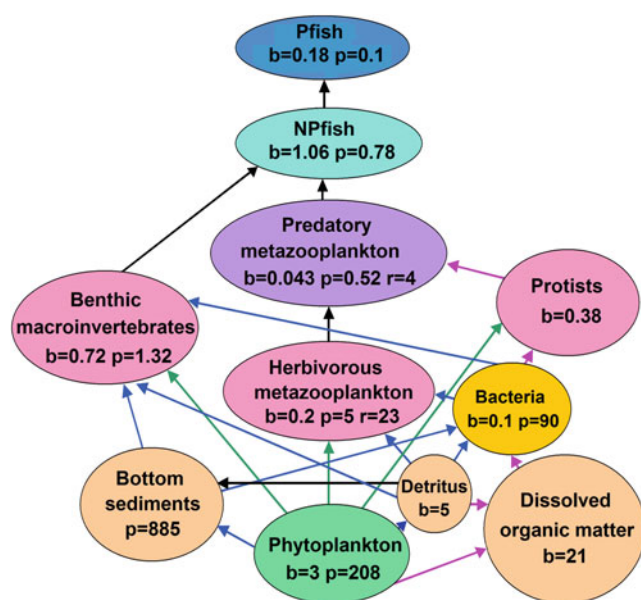
ciliates are able to graze daily more than 100% of the bacterial biomass production, and 9.3% of the bacterial and 20.7% of the nanophytoplankton standing stock, whereas metazooplankton grazes only a minor part of the standing stocks of bacterioplankton and nanoalgae (0.1% and 1%, respectively).

Research

The first data on Võrtsjärv fisheries, hydrology, and aquatic vegetation were published by Baltic German naturalists in the eighteenth and nineteenth centuries. The first monograph by Mühlen and Schneider (1920) was based on the complex expedition organized by the Lake Commission of the Estonian Naturalists' Society in 1911–1913. From the 1920s to 1950s, only a few investigations were carried out on Võrtsjärv. The bulk of the present long-term data on the lake has been collected during the existence of the Centre for Limnology (previously Võrtsjärv Limnological Station) since the 1960s. The results have been published in two monographs (Timm, 1973; Haberman et al., 2004) and numerous scientific papers. Võrtsjärv has been a case study lake in EU-scale research projects ECORAME, CLIME, and REFRESH. Võrtsjärv has been included in the World Lakes Database of the International Lake Environment Committee (ILEC) <http://www.ilec.or.jp/database/eur/eur-47.html>.

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Võrtsjärv Lake in Estonia, Figure 7 The quantified structure of the food web in Lake Võrtsjärv according to T. Nõges et al. (2004). Green arrows denote grazing food chains, blue arrows denote detrital food chains, violet arrows denote microbial loop, and black arrows denote other transformations. The same color of ovals denotes an equal distance from the base of the food chain – the same trophic level. Symbols: NPfish non-piscivorous fish, Pfish piscivorous fish, b bulk, g C m⁻², p production, g C m⁻² year⁻¹, r requested food ration, g C m⁻² year⁻¹.

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Cross-references

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Microorganisms in Lakes and Reservoirs
Nutrient Balance, Light, and Primary Production
Peipsi Lake in Estonia/Russia
Sedimentation Processes in Lakes
Submerged Vegetation in Shallow Lakes
Water Balance of Lakes

W

WATER BALANCE OF LAKES

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Description

The most basic in river basin hydrology is the water balance – and so it is for lakes. Most lakes have outflows, but some of the most famous lakes of the world are terminal lakes with no outflow, for example, the Caspian Sea, Lake Chad, and the Dead Sea. The water level in the overflowing lakes is rather stable, while the water level in the terminal lakes varies with the climate. In some lakes with small upstream catchment, the inflow to the lake is dominated by the precipitation on the lake, but usually inflow rivers are the dominating source of inflow to a lake. Some lakes only have subsurface inflow, but in most lakes, the most important inflow is from rivers. There also exist kettle lakes, which are part of the groundwater system with only subsurface inflow and outflow.

The water balance of a lake is

$$\begin{aligned}\frac{dVOL}{dt} &= A(h) \frac{dh}{dt} \\ &= Q_{in} - Q_{out}(h) + Q_{gwin} - Q_{gwout} + (P - E)A(h)\end{aligned}$$

VOL is the lake volume, A is the surface area which varies with the lake level, Q is surface flow, Q_{gw} is subsurface flow with different index for inflows and outflows, P is precipitation on the lake surface, and E is evaporation from the lake. There is seldom any groundwater seepage out of a lake. Groundwater inflow is significant when

there are springs or when the lake is situated on the border of an esker.

The natural river outflow is a function of the lake level above the outlet sill. If there is subsurface outflow, this subsurface outflow only very minor depends on the lake level. When the surface area and the outflow are known functions of the lake level, the lake level variation can be determined from the water balance. Most often the precipitation on the lake and the evaporation are nonsignificant compared to the inflows and outflows, so the water balance is simply

$$A(h) \frac{dh}{dt} = Q_{in} - Q_{out}(h)$$

Solving this equation with a short time step is called lake routing. The lake level and, from that, the outflow are determined. In a lake with outflow, the lake level, h, is usually given as the level above the outlet sill.

A lake with no outflow is a terminal lake and situated downstream in a closed basin, endorheic basin. Such a lake is a sink to most pollutants. The water is usually salty. Water leaves the lake only by evaporation. The water balance is

$$A(h) \frac{dh}{dt} = Q_{in} + (P - E)A(h)$$

The steady-state lake level area is then

$$A_{lake} = \frac{Q_{in}}{E - P}$$

The inflow is the basin precipitation – the evapotranspiration losses over the upstream basin – eventual water withdrawals. The lake is the lower part of a basin. If this endorheic basin including the lake has the area A_{basin} ,

the specific basin runoff is q , and if the lake has the variable surface area A_{lake} , then the part of the basin which constitutes the terminal lakes can be given as

$$\frac{A_{\text{lake}}}{A_{\text{basin}}} = \frac{q}{q + E - P}$$

Terminal lakes are found in dry climate. Often the lake area constitutes a not very small part of the river basin. Say the specific runoff is 100 mm/year, the lake evaporation 1,000 mm and the precipitation on the lake 500 mm. The lake area is then 20% of the river basin. In a warmer and drier period, the specific runoff may reduce to 70 mm, the evaporation may increase to 1,100 mm, and the precipitation may reduce to 400 mm. The lake area relative to the basin area then decreases to less than 10%, which means that the lake area is reduced 50%.

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Cross-references

Aral Sea
Caspian Sea
Nasser Lake
Poopó Lake, Bolivia
Volume of Water in Lakes and Reservoirs: Determination

WATER BALANCE OF THE LAURENTIAN GREAT LAKES

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Introduction

Surface water elevation dynamics of the Laurentian Great Lakes exhibit long-term persistence on decadal time scales, and the changes in surface water elevation over these time scales are driven mainly by climate dynamics.

Understanding Great Lakes water elevation dynamics on shorter time scales (such as monthly and annual scales) is commonly based on a cumulative assessment of the individual components of the net supply of water (i.e., precipitation, evaporation, and runoff) within the Great Lakes basin.

Great lakes water levels

The surface water elevations (hereafter referred to as “water levels”) of the Great Lakes are closely monitored by both the United States (through NOAA’s National Ocean Service) and Canada (through the Canadian Hydrographic Service). Monthly mean lake-wide levels, obtained by averaging a subset of US and Canadian gauges from around the lakes, can be obtained from the US Army Corps of Engineers:

<http://www.lre.usace.army.mil/greatlakes/hh/greatlakes/waterlevels/>

Figure 1 illustrates how lake levels have changed over time from 1948 to 2008. Water level data is available prior to 1948; however, we focus here on the 1948–2008 time period because it is the only period for which water levels and estimates for all components of net basin supply are readily available. Lake Michigan and Lake Huron have the same mean water level, as the lakes are connected at the Straits of Mackinac. Note that in Figure 1, we use a separate vertical axis for Lake Ontario, which is on average approximately 100 m lower than Lake Erie (due primarily to the drop in elevation over Niagara Falls). The thin, gray horizontal lines in Figure 1 indicate the long-term average water level for each lake from 1948 to 2008.

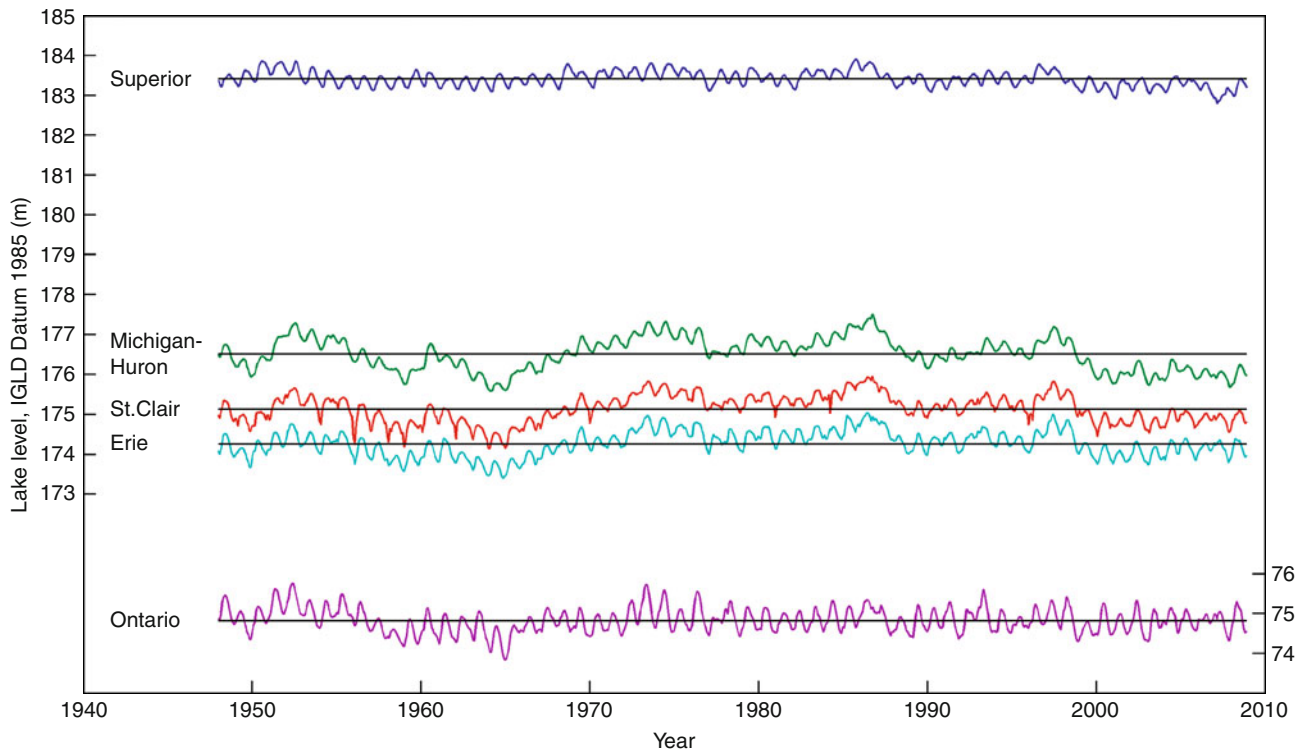
In general, water levels over the past decade were lower than the 1948–2008 average for all lakes but Lake Ontario. Long-term persistence on decadal time scales is also seen for all lakes, although more pronounced cycles are apparent for Lake Michigan-Huron. Lag-1 autocorrelation of mean annual levels ranges from 0.5 for Lake Ontario to 0.8 for Lake Michigan-Huron. Autocorrelation is in fact significantly larger than zero at the 95% level from lag-1 to lag-5 for Lake Michigan-Huron over this time period. These results collectively suggest a persistent, non-random pattern of annual water level on the Great Lakes.

Net basin supply

As with most lakes, the lake-wide average water level (H) of each of the Laurentian Great Lakes increases if the net total supply (NTS) of water to the entire basin (including the lake itself) is larger than the flow at the outlet of the lake (O). However, water level also varies with the temperature of the lake, which affects its density and, therefore, its volume. The change in water levels can therefore be expressed as follows (note that each term in the following expression, is in units of millimeter):

$$\Delta H = NTS - O + \Delta H_T$$

where ΔH_T reflects the impact of thermal expansion.



Water Balance of the Laurentian Great Lakes, Figure 1 Time series of Great Lakes monthly average lake-wide water levels, 1948–2008.

NTS can be decomposed into an overlake precipitation component (P), an overlake evaporation component (E), and a runoff component (R_{total}). The runoff component includes contributions from tributaries upstream of, and discharging directly into, each lake. This decomposition leads to the following expression:

$$\Delta H = P - E + R_{total} - O + \Delta H_T$$

Other terms of the water balance, such as consumptive use and net groundwater flux into the lakes, are relatively small compared to the components identified above, and are therefore generally ignored (IUGLS, 2009).

NTS can be further decomposed into runoff from the lake's own watershed (R), inflow coming from the upstream lake (I), and any nonnatural diversion of water into or out of adjacent watersheds (D). Hence:

$$\Delta H = P - E + R - O + I + D + \Delta H_T$$

The first three terms in the equation above correspond to the water cycle within a lake's individual basin, including the lake itself but not including the watershed of any upstream lake or diversion, and are collectively referred to as the net basin supply (NBS):

$$NBS = P - E + R$$

NBS is the primary driver of lake levels on monthly and longer time scales, as inflows and outflows are essentially

controlled by lake levels. Indeed, while Lake Superior and Lake Ontario outflows are regulated, which tends to reduce natural variability of lake levels, regulation has little impact on long-term trends: The climate, hence, essentially dictates what happens to lake levels, although other factors such as conveyance changes in the channels connecting the lakes and glacial isostatic adjustment do play a role (IUGLS, 2009). This relationship suggests that lake levels can be simulated and forecasted (Gronewold et al., 2011) on monthly time scales using monthly NBS sequences as input to a lake routing model in which regulation effects are predicted from lake levels, and diversions are prescribed.

The component and the residual methods

NBS can be computed by either estimating each of the three components P , E , and R (the component method), or as a residual of the water balance equation (the residual method), indicated in the following expression:

$$NBS = \Delta H + O - I - D - \Delta H_T$$

The thermal expansion term ΔH_T is generally ignored because it is close to zero on an annual time scale, but it can be significant on monthly time scales, given the strong annual cycle in water temperature. For example, according to Bruxer (2010), Lake Erie water levels increase on average by about 40 mm from May to July due to thermal expansion, and lose as much volume due

to thermal contraction between September and November, which corresponds to approximately 15% of the May-to-July *NBS*, but close to 40% of the September-to-November *NBS*.

Note that the residual method cannot be used to estimate separately *NBS* for Lake Michigan and Lake Huron, which are connected at the Straits of Mackinac. Hence, when it comes to assessing the water balance of the Great Lakes, Lake Michigan-Huron is generally considered to be a single body of water, although the component method can be used to obtain separate estimates of *NBS* for both lakes. A separate water balance is, however, commonly estimated for Lake St. Clair, so that *NBS* is generally computed for five lake systems: Lake Superior, Lake Michigan-Huron, Lake St. Clair, Lake Erie, and Lake Ontario. However, because Lake St. Clair and its watershed are significantly smaller than the other Great Lakes, it is often incorporated into the Lake Erie system, particularly in time series plots and other graphical representations of *NBS* and water levels.

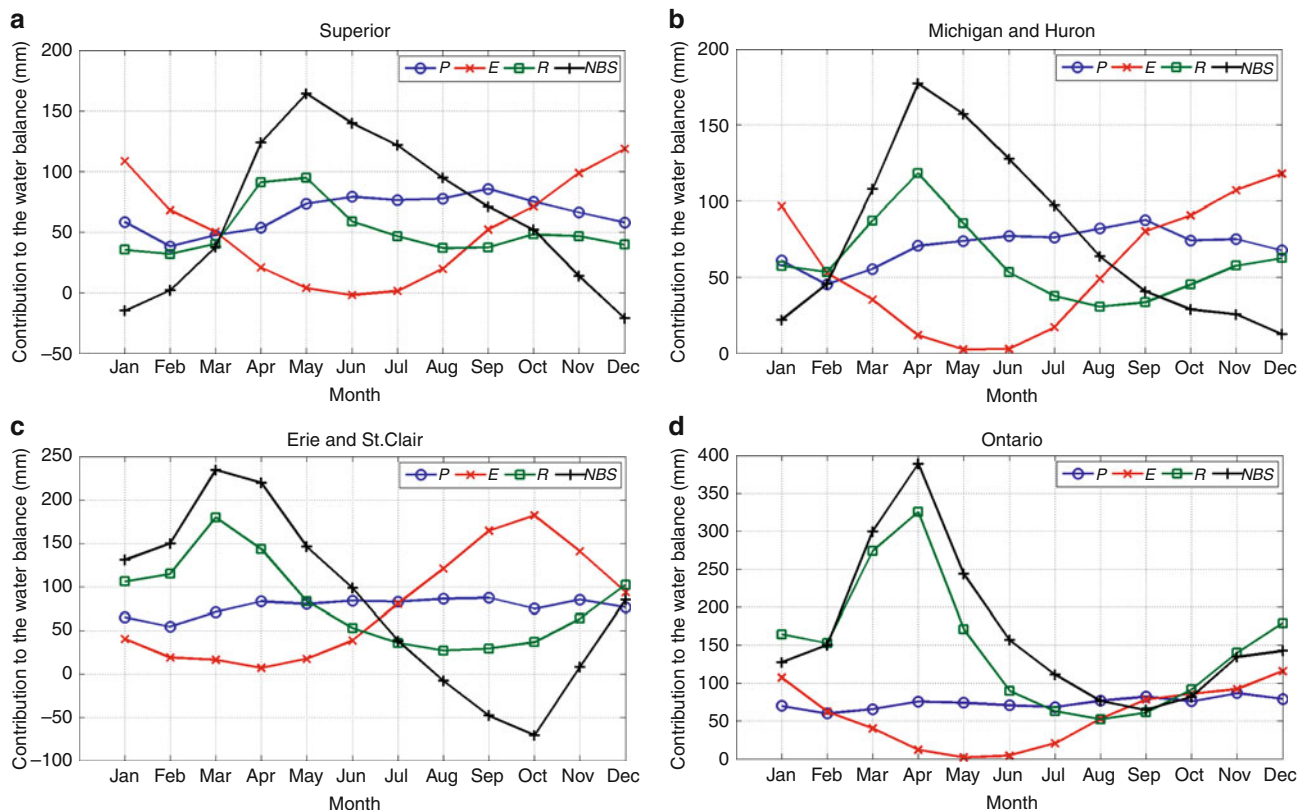
Components of net basin supply

Residual *NBS* can be computed from hydrological information alone (levels and flows); however, residual *NBS* estimates on time scales shorter than a month are often

highly uncertain and variable. The component *NBS* method requires a mix of meteorological and hydrological observations, integrated in a hydrometeorological model (Hunter and Croley, 1993; Pietroniro et al., 2007), in order to accurately estimate each component, but provides an additional level of understanding as to why lake levels change over time, and makes it possible to forecast *NBS* and lake levels on monthly to seasonal time scales (Gronewold et al., 2011). Long-term estimates of each *NBS* component, computed using techniques described by Hunter and Croley (1993), can be obtained from NOAA's Great Lakes Environmental Research Laboratory (GLERL):

<http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html>

Figure 2 includes GLERL's long-term (i.e., 1948–2008) average monthly *NBS* estimates and each of its components, and provides an indication of their seasonal dynamics. Results are shown for (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake Erie and St. Clair, and (d) Lake Ontario. It can be seen that the annual peak in *NBS* coincides with the annual peak in runoff for all lakes. For the Upper Great Lakes (all lakes but Lake Ontario), the annual minimum in *NBS* coincides with the annual peak in overlake evaporation.



Water Balance of the Laurentian Great Lakes, Figure 2 Average monthly net basin supply (NBS) and NBS components for the North American Laurentian Great Lakes, averaged over the period 1948–2008.

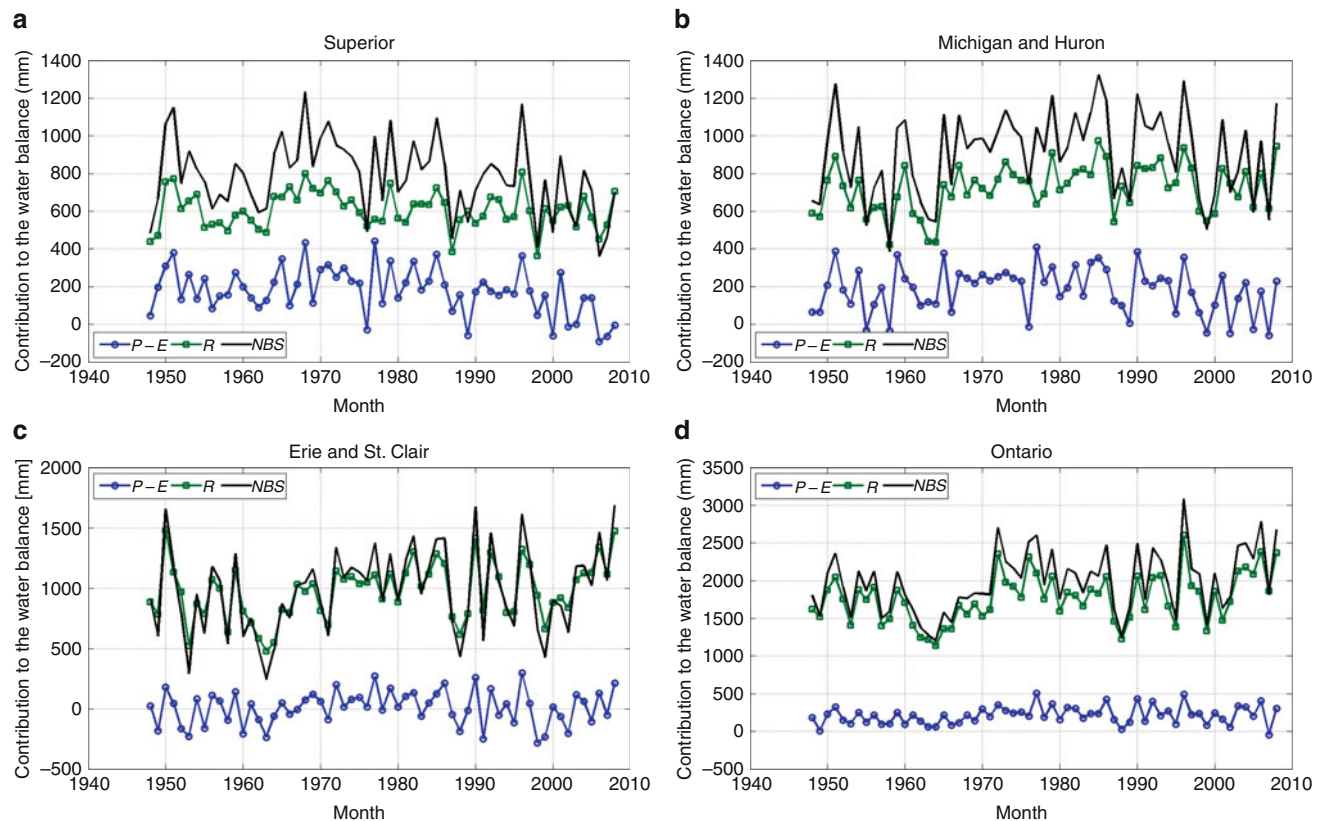
For all lakes, mean annual overlake precipitation is larger than mean annual overlake evaporation but, more importantly, mean annual runoff is larger than the mean annual net overlake precipitation ($P - E$). On an annual basis, the ratio of net overlake precipitation to NBS is, on average, roughly 20% for Lake Superior and Michigan-Huron, roughly 1% for Lake Erie and St. Clair, and roughly 10% for Lake Ontario. In all cases, the contribution of net overlake precipitation is much smaller than the ratio of the lake area to the watershed area. Hence, for the purpose of understanding and predicting the water balance of the Great Lakes on an annual scale, it is critical to accurately assess the runoff component. However, all three components can have a significant influence on NBS for individual months. In fact, NBS is often negative in fall and winter months, with overlake evaporation being larger than $P + R$.

Natural variability, uncertainty, and climate change

Figure 3 includes annual mean net overlake precipitation ($P - E$), runoff, and NBS for each lake from 1948 to 2008, and indicates a general decrease in annual net overlake precipitation ($P - E$) for Lakes Michigan-Huron

and Superior over the last several decades, with a noticeable increase in the frequency of negative net overlake precipitation for these two systems from roughly 2000 to 2008. On Lake Ontario, 2007 was the first year, for the period 1948–2008, with negative net overlake precipitation.

Important differences are in fact seen in NBS from one decade to the next for all lakes, and reflecting these dynamics in simulation and forecasting models is an important aspect of Great Lakes water resources management and planning. Shifting-level models, for example, have been used to describe, simulate, and predict NBS for water management purposes (Sveinsson et al., 2005; Fagherazzi et al., 2005), and represent a family of stochastic models that allows the mean of key process variables to change abruptly over time. Other modeling applications, including a time series segmentation algorithm based on the shifting-level model (Kehagias and Fortin, 2006), reveal that all lakes but the smaller Lake St. Clair have seen an upward shift in evaporation. This increase in evaporation is consistent with observed decreases in seasonal ice cover on all lakes (IUGLS, 2009), a phenomenon which can lead to increased heat input into the lake (Desai et al., 2009).



Water Balance of the Laurentian Great Lakes, Figure 3 Total annual net basin supply (NBS) and NBS components for the North American Laurentian Great Lakes for the period 1948–2008.

Figures 2 and 3 underscore the strong link between runoff and *NBS* for all lakes. Less obvious is the fact that net overlake precipitation adds variability to the signal. Indeed, the coefficient of variation of *NBS* (i.e., the standard deviation of *NBS* divided by its mean), is higher than the coefficient of variation of runoff for all lakes. Autocorrelation is therefore also lower for *NBS* than for runoff. The autocorrelation of annual runoff is in fact significantly different from zero at the 95% level for all lakes, but not the autocorrelation of annual *NBS*, suggesting that some of the persistence at the annual scale can be explained by the filtering effect of the watershed, although this signal could also be related to persistence in overland precipitation or evapotranspiration. This is consistent with the findings of Vogel et al. (1998), who found that annual streamflow records in the Great Lakes region showed higher persistence than in any other region of the conterminous United States.

All diagnostics based on the component *NBS* method are, however, limited by the accuracy with which each component is estimated. Indeed, the estimates we present here are simply one set of estimates, based on one set of model assumptions and one set of input data. Other model alternatives and data sources could be (and, increasingly, are being) used. Overlake precipitation, for example, can be estimated from near-shore precipitation gauges, radar and satellite imagery, and other sources, while runoff can be estimated from streamflow observations or conceptual rainfall-runoff models, although each method has unique intrinsic sources of uncertainty and variability (Neff and Nicholas, 2005). There is however no operational observational network on which to base estimates of overlake evaporation, and therefore, these estimates are based on hydrometeorological models calibrated to other observed variables, such as water surface temperature. Recent observations using an eddy-correlation system installed on a light house on Lake Superior (Blanken et al., 2011; Spence et al., 2011) suggest, however, that current operational models being used to assess overlake evaporation tend to overestimate evaporation in winter, and in particular when the latent heat flux is strongest, but do capture the synoptic-scale fluctuations in overlake evaporation. Even after accounting for this potential bias, however, there is a strong evidence of a recent increase in annual overlake evaporation within the Great Lakes basin.

As indicated previously, relatively recent increases in overlake evaporation and other *NBS* component dynamics are likely related more to shifting climate dynamics over decadal time scales than to seasonal or annual variability. Recent efforts to predict future *NBS* dynamics under alternative climate scenarios, including the use of hydrometeorological models forced by general circulation models, suggest a broad range of potential future *NBS* sequences and water levels (Angel and Kunkel, 2010). These models, however, may not appropriately represent basin evapotranspiration over decadal time scales (Lofgren et al.,

2011) and more precise climate-related *NBS* and Great Lakes water level projections might be expected from regional climate model simulations, many of which were recently conducted by both the United States and Canada as part of the International Upper Great Lakes Study (IUGLS, 2009).

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Cross-references

Great Lakes, North America

Laurentian Great Lakes, Interaction of Coastal and Offshore Waters

Water Balance of Lakes

WATER EXCHANGE BETWEEN LITTORAL ZONE AND OPEN LAKE WATER

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Definition

Exchange flow – Predominantly horizontal countercurrent flows.

Density-driven flow – A flow driven by predominantly horizontal density gradients. Synonyms include gravity current and buoyancy-driven flow.

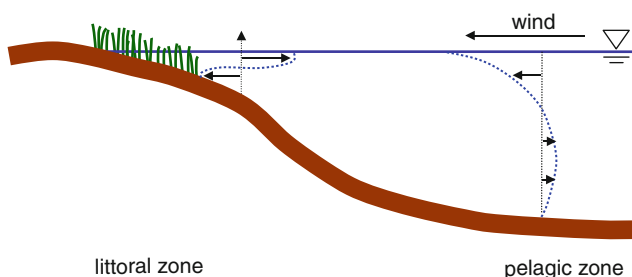
Thermally driven current – A gravity current in which the density gradient is the direct result of a spatial gradient in temperature.

Introduction

Adjacent littoral and pelagic (open) waters may have very different physical and chemical properties because of differences in proximity to land, depth, and vegetation density. For example, dissolved oxygen and pH were distinctly lower within a *Glyceria aquatica* stand in a pond than in the adjacent open water (Dvorák, 1970). Gradients have also been reported in turbidity, conductivity, alkalinity, and concentrations of various chemical constituents, such as Cl, K, Na, NO₃-N, total phosphorus, PO₄-P, and dissolved organic carbon across the littoral zone (Cardinale et al., 1997; James and Barko, 1991; Ng et al., 2010; Klosowski, 1992). In the presence of such long-range spatial gradients, advection between littoral and pelagic regions results in the net flux of constituents and physical properties over large distances.

Two types of exchange flows

The two main types of littoral–pelagic exchange flow in a lake are flows driven by stress imposed on the water surface by the wind and flows driven by a horizontal gradient in water temperature (Figure 1). The latter are commonly referred to as thermally-driven flows or gravity currents. In a closed system, these flows are accompanied by flow in the opposite direction so that mass is conserved.



Water Exchange Between Littoral Zone and Open Lake Water, Figure 1 An exchange flow between the pelagic zone and the littoral zone may be driven by wind-induced stress at the water surface or a littoral–pelagic temperature gradient. In this illustration, the wind and the density gradient due to the temperature difference drive flow in opposite directions.

Wind-driven surface currents

Wind blowing over the surface of a lake induces stress, driving water below it in the same direction. The speed of the wind-driven flow decays with increasing depth, then reverses direction, as illustrated in Figure 1.

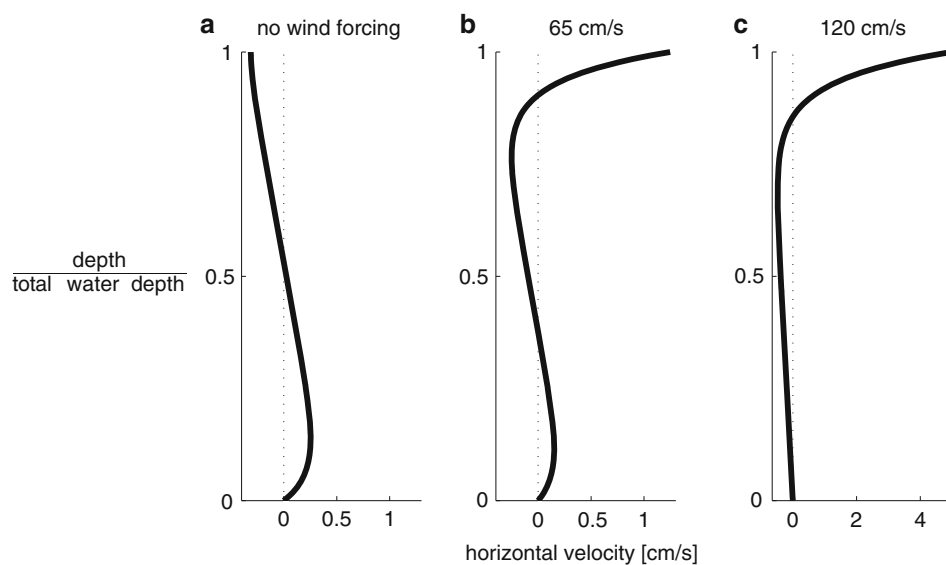
The speed of a wind-driven surface current is expected to increase with increasing wind speed, with 2% often cited as a typical ratio. Indeed, wind factors in the range 1.0–2.0% have been reported in selected field sites in the presence of winds at 1–6 m/s (Haines and Bryson, 1961; George, 2000, 1981). Further, several studies have reported the existence of a critical wind speed at which the surface current speed becomes constant (George, 2000) or begins to decrease sharply (Haines and Bryson, 1961). In Lake Mendota, Wisconsin, the critical wind speed was 5.7 m/s, with a corresponding surface current speed of 16.0 cm/s (Haines and Bryson, 1961). In Esthwaite Water in Cumbria, the critical wind speed was 3 m/s (George, 2000). In a more extreme case, surface current speeds in Eglwys Nynydd reservoir in Port Talbot were constant above a wind speed as low as 2 m/s (George and Edwards, 1976).

Thermally-driven flows

In inland aquatic systems, gradients in temperature, hence density, commonly arise from spatial variability in water depth (e.g., Monismith et al., 1990; Roget and Colomer, 1996), groundwater discharge (Roget et al., 1993), light compensation depth (e.g., MacIntyre et al., 2002; Nepf and Oldham, 1997), shading by floating macrophytes (Coates and Ferris, 1994; Dale and Gillespie,

Water Exchange Between Littoral Zone and Open Lake Water, Table 1 Selected field studies reporting thermally driven currents

Site	Conditions	Current speeds	Attributed origin of current	Reference
Eau Galle Reservoir, WI	Nighttime, calm conditions	0.1 cm/s intrusion current; 0.03, 0.05 cm/s surface return flow	Differential nighttime cooling	James and Barko, 1991
Lake Krankesjön, Sweden	Clear, summer, daytime, 0.5–2.2 m/s winds	0.1–2.3 cm/s surface flow toward littoral region	Temperature difference of 0.5–1.2°C across the littoral–pelagic interface. Open water is warmer	Lovstedt and Bengtsson, 2008
Clear Lake, CA	Summer, daily wind speed variations between 0 and 10 m/s	Thermally-driven flows of up to 10–15 cm/s	Diel oscillation between thermally-driven (night to early morning) and wind-driven circulation (daytime)	Rueda et al., 2003
Lake Banyoles, Catalonia	Overturn	1–10 cm/s bottom currents	Differential cooling. Variations in bottom current speed controlled by wind direction and speed	Roget et al., 1993

**Water Exchange Between Littoral Zone and Open Lake Water, Figure 2** Vertical profiles of flow velocity, as described by a mathematical solution for laminar flow conditions in an idealized, sparsely vegetated littoral region with a horizontal temperature gradient of 25°C/km (Tanino, 2004). The ordinate is distance from the bed normalized by the total water depth. The density gradient is negative, i.e., denser (cooler) water is to the left. Wind velocity is positive, with speeds as indicated above each profile.

1976) and dense canopy of reeds (Lovstedt and Bengtsson, 2008), or sheltering from the wind (MacIntyre et al., 2002). In the example illustrated in Figure 1, the temperature of the water in the shallower littoral zone increases more rapidly during daytime from solar radiation than that of the open water, and a horizontal temperature gradient develops between the littoral zone and the pelagic zone. As the littoral water warms, it becomes less dense and propagates toward the open water along the surface. The adjacent cooler water flows in below it in the opposite direction to conserve mass, thus establishing a circulation cell. At nighttime, the littoral water, which cools faster, flows toward the pelagic region as a bottom current.

Thermally-driven motion is generally regarded to be small compared to wind-induced currents. However, the

former may be significant when wind-induced flows are small. For example, in Esthwaite Water, surface currents at a given wind speed were 0.2–2 cm/s greater when a near-surface thermocline was established in the littoral region (George, 2000). These periods coincided with calm, warm conditions – when the open water was several degrees cooler than the littoral water – which are conditions favorable to thermally-driven flows. If the increase in current speed is interpreted to be due to thermally driven motion, then George (2000)’s observations indicate that thermally driven flows can exceed wind-induced flows. Also, conditions to induce thermally-driven flow may occur frequently during favorable seasons (e.g., James et al., 1994). For these reasons, thermally-driven flows may constitute an important pathway in lake-scale

chemical cycles despite their low velocities. For example, the net flux of total phosphorus attributed to nighttime convective circulation in July was estimated to correspond to 22% of the mean summertime lake-wide internal loading in Eau Galle Reservoir (James and Barko, 1991).

Selected field studies are listed in Table 1.

Direct interference of wind on thermally-driven flows

The interaction of wind and thermally-driven flows is inherently complex. The simplest arises from the requirement that the stress at the air/water interface must equal the wind stress. In the absence of wind, the density gradient creates a two-layered system with an undercurrent and surface current propagating in the positive and negative direction, respectively (e.g., Figure 2a). When wind stress acts in the same direction as the thermally-driven surface current, it merely increases the flow speed. When the wind stress acts against the surface current, the possible outcomes are more varied. Sufficiently low wind stress simply reduces the water speed at the surface. Sufficiently high wind stress will override the underlying thermally-driven circulation and induce a surface current in the downwind direction (Figure 2c). The behavior of the flow at intermediate wind stress is not obvious. For example, a mathematical solution of an idealized system, under laminar flow conditions within a region of homogeneous sparse vegetation, predicts a three-layered flow structure (Figure 2b).

Such interactions between wind stress and underlying thermally-driven motion were proposed to explain the diel variation in a density-driven bottom current from the shallow, persistently cooler northern lobe to the deeper southern lobe in Lake Banyoles, Catalonia (Roget et al., 1993). When the wind blows in the opposite direction as the bottom current, a single circulation cell is expected to develop across the two lobes, with wind stress enhancing the preexisting northward surface return current. When the wind blows southward, Roget et al. (1993) proposed a lake-scale circulation comprised of two cells. The first comprises the thermally-driven bottom current and a return current that flows immediately above it. This return current flows parallel to the sloping bed, emerging at the surface within the northern lobe. The second cell comprises a wind-driven surface current southward and a return flow above the return flow of the first circulation cell.

Summary

Exchange of water between the littoral and pelagic zones of a lake is predominantly driven by wind stress and horizontal gradients in temperature that may arise from differential heating and cooling. The contribution from the wind typically dominates, but significant thermally-driven flows have been observed in selected sites under calm conditions. The interaction of wind and thermally driven motion can give rise to complex circulation patterns.

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Cross-references

Circulation Processes in Lakes

Hydrodynamics of Very Shallow Lakes

Internal Seiches

Laurentian Great Lakes, Interaction of Coastal and Offshore Waters

Stratification in Lakes

Submerged Vegetation in Shallow Lakes

Thermal Regime of Lakes

Turbidity Currents in Reservoirs

WATER FRAMEWORK DIRECTIVE

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Definition

European-wide legislative framework seeking more integrated, rationalized, and sustainable management of water in the twenty-first century

Context and background

Water management is one of the oldest and most established areas of environmental policy in the European Union (EU). Starting in the 1970s, EU water policy evolved from an initial concern for the protection of human health via common drinking water standards. In the late 1980s, the focus moved toward the aquatic environment itself and the use of emission limit values (ELVs). Finally, from the mid-1990s onward, policy was reoriented toward the development of a more holistic and strategic approach that recognizes the interconnections between surface and ground water, water quantity and quality, and the impacts of land-based activities on the water environment (McCormick, 2001).

The Water Framework Directive (WFD) is the centerpiece of the EU's integrated approach to water protection and management. It is expected to provide the basic policy framework for most of the twenty-first century, albeit with modifications as experience is gained and new requirements emerge in response to climate change and human uses of water. Formally adopted as EU policy in 2000, the WFD aims to protect all inland and coastal surface waters and groundwater; to achieve good ecological, chemical, and quantitative status for waters by 2015; to establish a system of water management based on river basin units; to combine ELVs with environmental quality standards; to ensure water prices provide adequate incentives to secure efficient uses of water; to involve

citizens more closely in decision making; and to streamline legislation (European Community (EC), 2007). Two additional areas needing new and more specific legislation were identified within the WFD: Priority Substances (Article 16) and Groundwater (Article 17). A new Groundwater Directive (2006/118/EC) was adopted in December 2006, and a Priority Substances Directive (2008/105/EC) was agreed in December 2008. The scope of the WFD has been further extended with the adoption of a Directive on the assessment and management of floods (2007/60/EC) and a Marine Strategy Framework Directive (2008/56/EC).

Implementation of the WFD

An implementation timetable was detailed within the text of the WFD, specifying deadlines by which key stages of the Directive should be achieved within Member States. Despite this Europe-wide plan for implementation, the success and technical content of the implementation process has differed substantially among individual Member States (EC, 2007). Implementation of the WFD requires that Member States:

Identify river basin districts and competent authorities

Management under the WFD is organized at the spatial scale of River Basin Districts (RBDs), perceived as a natural spatial unit for holistic and coordinated management of land and water. Member States were required to define RBDs on the basis of river catchments, using surface-water hydrological divides to identify the area of land from which water drains to a river. Across the EU, RBDs vary from single river catchments to combinations of multiple river catchments, and from less than 1,000 km² to over 800,000 km², with 40 RBDs crossing international borders and necessitating collaboration between Member States to deliver coordinated management at the RBD scale (EC, 2007). Competent authorities (CAs) responsible for administering the WFD have been identified for each RBD, with arrangements varying from one CA per RBD, through multiple CAs per RBD, to one CA for multiple RBDs (EC, 2007).

Identify water bodies, typologies, and reference conditions

Individual water bodies (WB) are defined within each RBD, and across the EU, 70,000 surface WBs have been identified of which approximately 15% are lakes (EC, 2007). Water bodies are categorized under the WFD as a lake, reservoir, stream, river or canal, part of a stream, river or canal, a transitional water, stretch of coastal water, or volume of groundwater (EC, 2000). Typology schemes are outlined for each WB category within the WFD, enabling Member States to group WBs with similar natural characteristics into a smaller number of water body types. For example, lake WB typologies are based largely on physical characteristics, including altitude, depth, and size

(EC, 2000). Separate WB categories exist for artificial and for heavily modified WBs. Heavily modified WBs are those where significant modification to the physical characteristics of the WB has occurred, and where the changes required to meet default objectives under the WFD would significantly adversely affect one or more human uses of that WB (UKTAG, 2008). Some Member States have designated over 50% of their WBs as heavily modified (EC, 2007), with implications for the objectives sought for these WBs (see below). Water body type-specific reference conditions must be defined under the WFD, against which the current status and future change in status of a WB are assessed. Reference conditions define biological, physicochemical, and hydromorphological conditions within a WB type in the absence of significant human pressure, and have been identified through analysis of existing non-impacted sites, through modeling, or through expert judgment.

Characterize pressures

Within each RBD, an assessment of the significant human-induced pressures acting on a WB, and the consequent risk that the WB will fail to meet the default objectives of the WFD, has been made. These risk assessments have demonstrated that approximately 40% of surface WBs across the EU are at risk of failing to achieve the default WFD objectives, but that this figure exceeds 70% in a number of Member States (EC, 2007). The pressures responsible for the risks of failure are diverse, including point and diffuse source pollution, morphological and hydrological modification, and the presence of alien species, and are derived from a range of activities spanning flood defense, mining, agriculture, urban development, and power generation. Limited data meant that the first risk assessment for 30% of the surface WBs across Europe was inconclusive (EC, 2007).

Monitor and classify the status of water bodies

The status of surface WBs under the WFD is defined by two components: ecological and chemical status. The ecological status classification is given by the lowest classed element from assessment of: biological quality elements (in lakes including fish, benthic macroinvertebrate, and phytoplankton communities); hydromorphological quality elements; and general chemical and physicochemical quality elements that support the biological quality elements, such as dissolved oxygen and total phosphorus concentrations in lakes (UKTAG, 2009). Chemical status is defined using a pass/fail system against environmental quality standards for priority substances and other EU-level dangerous substances, with the lowest classed substance determining chemical status. Overall surface water status under the WFD is given by the lower of either ecological or chemical status. This is a demanding classification scheme in which a failure to meet WFD objectives for one quality element results in an overall failure of the WB. Implementation of this classification scheme in the first planning cycle of the

WFD indicated that many WBs across Europe currently fail to meet the status required under the WFD. For example, within the Humber RBD in England, only 18% of surface WBs were classified as being at good status in 2009 (Environment Agency, 2009). Data for classification of WBs are provided by monitoring networks established within each Member State. *Surveillance monitoring* involves collection of data for all quality elements that contribute to status classification for a WB type, and builds on existing monitoring networks in Member States. *Operational monitoring* focuses on quality elements believed to be most sensitive to the pressures acting on a WB, and is designed to classify a WB at risk of failing to meet the objectives of the WFD. *Investigative monitoring* responds to unplanned events, such as pollutant spills, and is also used where the cause of a failure in a WB is not well understood (UKTAG, 2009).

Agree objectives and programmes of measures

The minimum requirement under the WFD is to prevent any further deterioration in the status of WBs. Beyond this, default objectives for each WB are defined. For surface WBs, this is to achieve good ecological and chemical status by 2015, and for groundwater bodies, good chemical and quantitative status by 2015. For artificial or heavily modified WBs, the default WFD objective is to achieve good ecological potential by 2015. Ecological potential is assessed using the mitigation measures that are in place to reduce the hydromorphological pressures on a WB. Where all applicable measures are in place, the WB is classified as being at good ecological potential or above; where one or more measure is not currently in place, the WB is classified as less than good ecological potential (UKTAG, 2008). If achieving default objectives under the WFD is deemed to be either technically infeasible or disproportionately costly (see below), alternative objectives can be defined. These include setting an objective that is lower than good status, or extending the timescale over which good status is achieved. For WBs that are already classified as being at good or better ecological status/potential, the WFD requirement of no deterioration in status applies. Protected area status under the WFD can be given to areas to safeguard their use (e.g., in the supply of drinking water), or because they contain important habitats or species. These areas are managed to deliver WFD objectives alongside existing objectives derived from previous EC legislation, such as the Habitats or Freshwater Fish Directives. Management actions to be undertaken as part of the WFD are defined as measures, and a programme of measures needs to be created for each RBD to ensure WB objectives are achieved. The WFD allows for economic and social appraisal of these measures (see below). It is on the basis of these appraisals that the measures needed to achieve good ecological status/potential can be classified as technically infeasible or disproportionately costly, offering the opportunity to set alternative objectives.

Conduct economic appraisals and apply economic instruments

Economic analysis is a significant feature of the implementation process, and references to economic principles (e.g., polluter pays), approaches (e.g., cost-effectiveness analysis), and tools (e.g., water pricing) appear throughout the text of the WFD. A detailed and robust economic analysis of water use and management is regarded as an essential aid to decision making (EC, 2003a), which not only will inform the preparation of the plans under the WFD but will also help to justify the basic and supplementary actions included in the programme of measures. Under Article 5, an analysis of water uses within each RBD was required (by 2004), with information required on the economic importance of water uses, projected trends and associated costs of water uses to 2015, and current levels of cost recovery for the range of water services. The results of the economic analysis are used within the river basin characterization process and are subsequently presented in the plans for each RBD. In cases where significant water management issues and/or risks of noncompliance with ecological, chemical, or quantitative objectives are identified from the characterization process, additional economic analysis is required as an integral part of the development of a programme of measures. Furthermore, the scope of the programme of measures is extended to include the recovery of the costs of water services, including environmental costs, under Article 9. Under this provision, water pricing arrangements must be put in place to provide incentives for efficient water use and different categories of water users (agriculture, domestic, industry) must contribute to the recovery of costs by 2010. The programme of measures includes two elements: (1) basic measures which comprise of existing EU Directives plus national standards, regulations, registers, and permitting arrangements, and (2) supplementary measures which include additional regulatory, economic, or voluntary measures which may be necessary to achieve the objectives specified for the WBs within a RBD. Each proposed measure, and the overall programme of combined measures, must be subjected to a cost-effectiveness analysis in order to demonstrate its viability. In cases where elements are shown not to be economically justified, the programme of measures must be adjusted accordingly. Under Article 4, the results of this analysis may also be used to seek derogations (time extensions and/or lower environmental objectives, see above) if it is shown that the implementation of the programme of measures would have serious economic or social impacts. Similarly, the economic analysis can be used to seek exemptions to avoid restoring heavily modified WBs where the costs could substantially outweigh the benefits.

Produce river basin management plans through an iterative planning process

The outcomes of the planning process described above need to be recorded for each RBD within a River Basin Management Plan (RBMP). The RBMP has no statutory

power in itself but should seek to set the framework within which existing powers are exercised to deliver the objectives of the WFD. A RBMP should: (1) provide an overview of the objectives for each WB and the programme of measures necessary to meet these objectives, (2) set the strategic policy framework for decisions affecting the water environment, and (3) report to the EC on implementation of the WFD (Defra, 2006). The river basin management planning process operates on an iterative 6-year cycle, involving assessment of WB status and pressures, drafting of RBMPs for consultation, implementation of measures, and review. The first RBMPs to emerge from this process were published in 2009, with subsequent plans due for publication in 2015, 2021, and 2027.

Provide information and enable public participation

The entire implementation process is to be conducted in an open and transparent manner, as this is believed to offer the strongest prospect of both commitment to action and environmental improvement. The 1998 Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters led to the adoption of EU Directive 2003/4/EC on public access to environmental information and EU Directive 2003/35/EC on providing for public participation in environmental plans and programmes. The provisions of both of these Directives are reflected in Article 14 of the WFD, which requires member states to encourage active involvement of all interested parties in the production, implementation, review, and updating of the RBMPs (EC, 2003b). For each RBD, the public must have access to and be able to comment on: (1) a timetable and work programme for the production of the RBMP, including details of the consultation process, at least 3 years ahead of the starting date for the plan; (2) an initial overview of the significant water management issues identified in the RBD at least 2 years before the starting date for the plan; and (3) draft copies of the RBMP at least 1 year ahead of the starting date. Furthermore, on request the public should have access to background documents and information used in the preparation of the draft RBMPs and be given at least 6 months to submit written comments.

Assessment of progress and future challenges

Although broadly recognized as an ambitious and distinctive piece of EC legislation, the basis of the WFD and the detail of the implementation process have been subjects for critical discussion in the last decade. The ecological ideology underpinning the WFD, particularly the use of reference conditions to define ecological status, has been argued to be philosophically and pragmatically problematic because it fails to recognize humans as integral to, rather than external pressures on, ecosystems (Dufour and Piégay, 2009). While placing ecological principles at the heart of EC legislation is revolutionary, implementation of the WFD has focused strongly on traditional structural approaches to ecological

assessment (Basset, 2010). Consequently, the ecological potential of the WFD has failed to be realized, and important characteristics of ecological quality, including nutrient parsimony and connectivity between ecosystems, have not been incorporated in the implementation process (Moss, 2008). Identifying sites at reference condition in Europe is challenging, particularly for heavily human-impacted systems such as lowland rivers, and pristine sites that are considered as reference sites may actually have been significantly altered, for example, by atmospheric pollution (Hamilton et al., 2010). Impacts associated with future climate change may render reference conditions irrelevant, or require revision of these conditions during later cycles of the WFD (Noges et al., 2009). Distinguishing human impacts on an ecosystem from changes due to natural variability remains difficult (Hatton-Ellis, 2010) and is exacerbated by limited data records that do not enable natural variability to be characterized robustly. The cause of failure within a WB and the response of a WB to mitigation measures depend on complex, multivariate cause-effect relationships, and current understanding of these complex systems is often insufficient to support the ambitious aims of the WFD (Solimini et al., 2009). The timescale of the WFD has been argued to be overambitious. Complex ecosystems are unlikely to show clear responses to mitigation measures during the 6-year planning cycles of the WFD (Hering et al., 2010), and achieving default WFD objectives by 2015 in heavily impacted systems is unlikely to be feasible. The WFD has also been argued to require a fundamental shift in the spatial scale of assessment and restoration activities, moving away from site-specific work toward larger-scale activity (Hamilton et al., 2010). Although intuitively attractive, these larger-scale activities are difficult to realize in practice. Despite the intercalibration exercises undertaken as part of the WFD, significant and largely unexpected variation across Europe in reference conditions, water body typologies, assessment, and monitoring strategies has developed (Hering et al., 2010). While indicative of the greater flexibility offered by the WFD compared to previous EC legislation, some have argued that this variation reflects difficulties associated with the lack of precise definitions offered by the Directive (Moss, 2008).

In addition to the technical and scientific challenges presented by the WFD, significant institutional and administrative obstacles have to be overcome, not least in the 40 international river basins within the EU. According to the 2007 assessment conducted by the European Commission (EC, 2007), poor legal transposition and the lack of economic analysis are the biggest implementation gaps so far, but actions are also required by Member States with respect to the effectiveness of public participation and the integration of sustainable water management into other policy areas such as agriculture and urban development. The capacities of the designated CAs to implement all of the WFD requirements vary enormously, along with political commitment and funding made available for planning and the implementation of the programmes of measures. As a consequence, a north-south divide has

emerged, with many of the southern Member States falling behind the implementation timetable. Concern has also been expressed that some Member States have set extremely ambitious objectives and proposed measures without full consideration of relevant costs. It is highly likely that achievements by 2015 will vary widely across the EU, since Member States and their designated CAs have different starting points, different technical and administrative capacities, and different levels of ambitions expressed in their draft RBMPs (Water Information System for Europe, 2009).

Summary

The Water Framework Directive (WFD) is designed to provide an integrated approach to water resources management and protection for the whole of the European Union (EU). Through an iterative planning and implementation process, the Member States are required to designate river basin districts and appoint competent authorities with responsibility for the WFD, establish reference conditions for different types of water bodies, assess current conditions and identify appropriate objectives and programmes of measures to achieve them. This information is to be presented in the form of a river basin management plan for each designated district, and the planning process itself must make extensive use of both economic analysis and public participation. The first cycle of river basin management plans published in 2009 show considerable variation in approach and compliance with WFD requirements across the EU, with some Member States falling behind the implementation schedule and others setting ambitious environmental targets without adequate consideration of the likely economic costs.

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Cross-references

- Climate Change: Factors Causing Variation or Change in the Climate
- Eutrophication in Fresh Waters: An International Review
- Water Quality in Lakes and Reservoirs

WATER QUALITY FOR DRINKING: WHO GUIDELINES

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Introduction

Water for drinking comes from one or more of these sources. In order to satisfy the quality of the water being of acceptable standard, the World Health Organization (WHO), an agency of the United Nations Organization, has provided international *Guidelines for Drinking-water Quality*.

Diseases related to contamination of drinking water constitute a major burden on human health, the greatest majority of water-related health problems being the result of microbial contamination (bacteriological, viral, protozoan). In general terms the greatest microbial risks are associated with ingestion of water that is contaminated with human or animal feces. Feces can be a source of pathogenic bacteria, viruses, protozoa, and helminths.

In addition to fecally borne pathogens, other microbial hazards such as guinea worm, toxic cyanobacteria, and *Legionella* may also be important under specific circumstances.

The primary purpose of the *Guidelines for Drinking-water Quality* is the protection of public health.

Water is essential to sustain life, and a satisfactory (adequate, safe, and accessible) supply must be available to all. Improving access to safe drinking water can result in tangible benefits to health. Every effort should be made to achieve a drinking-water quality as safe as practicable.

Safe drinking water, as defined by the Guidelines, does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages. Those at greatest risk of water-borne disease are infants and young children, people who are debilitated or living under unsanitary conditions, and the elderly. Safe drinking water is suitable for all usual domestic purposes, including personal hygiene. The Guidelines are applicable to packaged water and ice intended for human consumption. However, water of higher quality may be required for some special purposes, such as renal dialysis and cleaning of contact lenses, or for certain purposes in food production and pharmaceutical use. Those who are severely immunocompromised may need to take additional steps, such as boiling drinking water, due to their susceptibility to organisms that would not normally be of concern through drinking water. The Guidelines may not be suitable for the protection of aquatic life or for some industries.

The Guidelines are intended to support the development and implementation of risk management strategies that will ensure the safety of drinking-water supplies through the control of hazardous constituents of water. These strategies may include national or regional standards developed from the scientific basis provided in the Guidelines. The Guidelines describe reasonable minimum requirements of safe practice to protect the health of consumers and/or derive numerical “guideline values” for:

Microbes in water

Although the greatest risk from microbes in water is associated with consumption of drinking water that is contaminated with human and animal excreta, other sources and routes of exposure may also be significant.

This chapter focuses on organisms for which there is evidence, from outbreak studies or from prospective studies in non-outbreak situations, of disease being caused by ingestion of drinking water, inhalation of droplets, or contact with drinking water, and their control.

Microbial hazards associated with drinking water

Infectious diseases caused by pathogenic bacteria, viruses, and parasites (e.g., protozoa and helminths) are the most common and widespread health risk associated with drinking water. The public health burden is determined by the severity of the illness(es) associated with pathogens, their infectivity, and the population exposed.

Breakdown in water supply safety may lead to large-scale contamination and potentially to detectable disease outbreaks. Other breakdowns and low-level, potentially repeated contamination may lead to significant sporadic disease, but is unlikely to be associated with the drinking-water source by public health surveillance.

Quantified risk assessment can assist in understanding and managing risks, especially those associated with sporadic disease.

Waterborne infections

The pathogens that may be transmitted through contaminated drinking water are diverse. Table 1 provides general information on pathogens that are of relevance for drinking-water supply management. The spectrum changes in response to variables such as increases in human and

animal populations, escalating use of wastewater, changes in lifestyles and medical interventions, population movement and travel, and selective pressures for new pathogens and mutants or recombinations of existing pathogens. The immunity of individuals also varies considerably, whether acquired by contact with a pathogen or influenced by such factors as age, sex, state of health, and living conditions.

For pathogens transmitted by the fecal-oral route, drinking water is only one vehicle of transmission. Contamination of food, hands, utensils, and clothing can also play a role, particularly when domestic sanitation and hygiene are poor. Improvements in the quality and availability of water, in excreta disposal, and in general hygiene are all important in reducing fecal-oral disease transmission.

Microbial water quality verification

For microbial water quality, verification is likely to include microbiological testing. In most cases, it will involve the analysis of fecal indicator microorganisms, but in some circumstances it may also include assessment of specific pathogen densities. Verification of the microbial quality of drinking water may be undertaken by the supplier, surveillance agencies, or a combination of the two.

Water Quality for Drinking: WHO Guidelines, Table 1 Waterborne pathogens and their significance in water supplies

Pathogen	Health significance	Persistence in water supplies	Resistance to chlorine	Relative infectivity	Important animal source
Bacteria					
<i>Burkholderia pseudomallei</i>	Low	May multiply	Low	Low	No
<i>Campylobacter jejuni</i> , <i>C. coli</i>	High	Moderate	Low	Moderate	Yes
<i>Escherichia coli</i> – pathogenic ^d	High	Moderate	Low	Low	Yes
<i>E. coli</i> – enterohaemorrhagic	High	Moderate	Low	High	Yes
<i>Legionella</i> spp.	High	Multiply	Low	Moderate	No
Nontuberculous mycobacteria	Low	Multiply	Low	Low	No
<i>Pseudomonas aeruginosa</i> ^e	Moderate	May multiply	Moderate	Low	No
<i>Salmonella typhi</i>	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
<i>Shigella</i> spp.	High	Short	Low	Moderate	No
<i>Vibrio cholerae</i>	High	Short	Low	Low	No
<i>Yersinia enterocolitica</i>	High	Long	Low	Low	Yes
Viruses					
Adenoviruses	High	Long	Moderate	High	No
Enteroviruses	High	Long	Moderate	High	No
Hepatitis A virus	High	Long	Moderate	High	No
Hepatitis E virus	High	Long	Moderate	High	Potentially
Noroviruses and sapoviruses	High	Long	Moderate	High	Potentially
Rotaviruses	High	Long	Moderate	High	No
Protozoa					
<i>Acanthamoeba</i> spp.	High	Long	High	High	No
<i>Cryptosporidium parvum</i>	High	Long	High	High	Yes
<i>Cyclospora cayentanensis</i>	High	Long	High	High	No
<i>Entamoeba histolytica</i>	High	Moderate	High	High	No
<i>Giardia intestinalis</i>	High	Moderate	High	High	Yes
<i>Naegleria fowleri</i>	High	May multiply ¹	High	High	No
<i>Toxoplasma gondii</i>	High	Long	High	High	Yes
Helminths					
<i>Dracunculus medinensis</i>	High	Moderate	Moderate	High	No
<i>Schistosoma</i> spp.	High	Short	Moderate	High	Yes

Approaches to verification include testing of source water, water immediately after treatment, and water in distribution systems of stored household water. Verification of the microbial quality of drinking water includes testing for *Escherichia coli* as an indicator of fecal pollution and should not be present in drinking water. In practice, testing for thermotolerant coliform bacteria can be an acceptable alternative in many circumstances. While *E. coli* is a useful indicator, it has limitations. Enteric viruses and protozoa are more resistant to disinfection; consequently, the absence of *E. coli* will not necessarily indicate freedom from these organisms. Under certain circumstances, it may be desirable to include more-resistant microorganisms, such as bacteriophages and/or bacterial spores. Such circumstances could include the use of source water known to be contaminated with enteric viruses and parasites or high levels of viral and parasitic diseases in the community.

Water quality can vary rapidly, and all systems are subject to occasional failure. For example, rainfall can greatly increase the levels of microbial contamination in source waters, and waterborne outbreaks often occur following rainfall.

Drinking-water safety is not related only to fecal contamination. Some organisms grow in piped water distribution systems (e.g., *Legionella*), whereas others occur in source waters (guinea worm) and may cause outbreaks and individual cases. Some other microbes (e.g., toxic cyanobacteria) require specific management approaches, which are covered elsewhere in these Guidelines.

Certain serious illnesses result from inhalation of water droplets (aerosols) in which the causative organisms have multiplied because of warm temperatures and the presence of nutrients. These include legionellosis and Legionnaires' disease, caused by *Legionella* spp.

Schistosomiasis (bilharziasis) is a major parasitic disease of tropical and subtropical regions that is transmitted when the larval stage (cercariae), which is released by infected aquatic snails, penetrates the skin. It is primarily spread by contact with water. Ready availability of safe drinking water contributes to disease prevention by reducing the need for contact with contaminated water resources – for example, when collecting water to carry to the home or when using water for bathing or laundry.

Other pathogens that may be naturally present in the environment may be able to cause disease in people with impaired local or general immune defense mechanisms, such as the elderly or the very young, patients with burns or extensive wounds, those undergoing immunosuppressive therapy, or those with acquired immunodeficiency syndrome (AIDS). If water used by such persons for drinking or bathing contains sufficient numbers of these organisms, they can produce various infections of the skin and the mucous membranes of the eye, ear, nose, and throat.

Most of the human pathogens listed in Table 1 are distributed worldwide; some, however, such as those causing outbreaks of cholera or guinea worm disease, are regional. Eradication of *D. medinensis* is a recognized target of the WHO.

It is likely that there are pathogens not shown in Table 1 that are also transmitted by water. This is because the number of known pathogens for which water is a transmission route continues to increase as new or previously unrecognized pathogens continue to be discovered.

Infectious disease caused by pathogenic bacteria, viruses, protozoa, and helminths are the most common widespread health risk with drinking water.

Persistence and growth in water

While typical waterborne pathogens are able to persist in drinking water, most do not grow or proliferate in water. Microorganisms like *E. coli* can accumulate in sediments and are mobilized when water flow increases.

After leaving the body of their host, most pathogens gradually lose viability and the ability to infect. The rate of decay is usually exponential, and a pathogen will become undetectable after a certain period. Pathogens with low persistence must rapidly find new hosts and are more likely to be spread by person-to-person contact or poor personal hygiene than by drinking water. Persistence is affected by several factors, of which temperature is the most important. Decay is usually faster at higher temperatures and may be mediated by the lethal effects of UV radiation in sunlight acting near the water surface.

The most common waterborne pathogens and parasites are those that have high infectivity and either can proliferate in water or possess high resistance to decay outside the body.

Public health aspects

Outbreaks of waterborne disease may affect large numbers of people, and the first priority in developing and applying controls on drinking-water quality should be the control of such outbreaks. Available evidences also suggest that drinking water can contribute to background disease in non-outbreak situations, and control of drinking-water quality should therefore also address waterborne disease in the general community.

Experience has shown that systems for the detection of waterborne disease outbreaks are typically inefficient in countries at all levels of socioeconomic development, and failure to detect outbreaks is not a guarantee that they do not occur; nor does it suggest that drinking water should necessarily be considered safe.

Some of the pathogens that are known to be transmitted through contaminated drinking water lead to severe and sometimes life-threatening disease. Examples include typhoid, cholera, infectious hepatitis (caused by hepatitis A virus [HAV] or HEV), and disease caused by *Shigella* spp. and *E. coli* O157. Others are typically associated with less-severe outcomes, such as self-limiting diarrheal disease (e.g., Norovirus, *Cryptosporidium*).

The effects of exposure to pathogens are not the same for all individuals or, as consequence, for all populations. Repeated exposure to a pathogen may be associated with a lower probability of severity of illness because

of the effects of acquired immunity. For some pathogens (e.g., HAV), immunity is lifelong, whereas for others (e.g., *Campylobacter*), the protective effects may be restricted to a few months to years. On the other hand, sensitive subgroups (e.g., the young, the elderly, pregnant women, and the immunocompromised) in the population may have a greater probability of illness, or the illness may be more severe, including mortality. Not all pathogens have greater effects in all sensitive subgroups.

Not all infected individuals will develop symptomatic disease (including carriers), which differs between pathogens and also depends on population characteristics, such as a prevalence of immunity.

To a large extent, people have no means of judging the safety of their drinking water themselves, but their attitude toward their drinking-water supply and their drinking-water suppliers will be affected to a considerable extent by the aspects of water quality that they are able to perceive with their own senses. It is natural for the consumers to regard with suspicion water that appears dirty or discolored or that has an unpleasant taste or smell, even though these characteristics may not in themselves be of direct consequence to health.

The provision of drinking water that is not only safe but also acceptable in appearance, taste, and odor is of high priority. Water that is aesthetically unacceptable will undermine the confidence of consumers, lead to complaints, and, more importantly, possibly lead to the use of water from sources that are less safe.

It is important to consider whether existing or proposed water treatment and distribution practices can affect the acceptability of drinking water. For example, a change in disinfection practice may generate an odorous compound such as trichloramine in the treated water. Other effects may be indirect, such as disturbance of internal pipe deposits and biofilms when changing between blending waters from different sources in distribution systems. The appearance, taste, and odor of drinking water should be acceptable to the consumer.

The WHO guidelines are applicable to large metropolitan and small community piped drinking-water systems and to non-piped drinking-water systems in communities and in individual dwellings. The guidelines are also applicable to a range of specific circumstances, including large buildings, travelers, and conveyances.

The great majority of evident water-related health problems are the result of microbial (bacteriological, viral, protozoan, or other biological) contamination. Nevertheless, an appreciable number of serious health concerns may occur as a result of the chemical contamination of drinking water.

Microbial aspects

Securing the microbial safety of drinking-water supplies is based on the use of multiple barriers, from catchment to consumer, to prevent the contamination of drinking water or to reduce contamination to levels not injurious to health. Safety is increased if multiple

barriers are in place, including protection of water resources, proper selection and operation of a series of treatment steps, and management of distribution systems (piped or otherwise) to maintain and protect treated-water quality. The preferred strategy is a management approach that places the primary emphasis on preventing or reducing the entry of pathogens into water sources and reducing reliance on treatment processes for removal of pathogens.

In general terms, the greatest microbial risks are associated with ingestion of water that is contaminated with human or animal (including bird) feces. Feces can be a source of pathogenic bacteria, viruses, protozoa, and helminths.

Failure to ensure drinking-water safety may expose the community to the risk of outbreaks of intestinal and other infectious diseases. Drinking-water-borne outbreaks are particularly to be avoided because of their capacity to result in the simultaneous infection of a large number of persons and potentially a high proportion of the community.

In addition to fecally borne pathogens, other microbial hazards (e.g., guinea worm [*Dracunculus medinensis*], toxic cyanobacteria, and *Legionella*) may be of public health importance under specific circumstances.

The infective stages of many helminths, such as parasitic roundworms and flatworms, can be transmitted to humans through drinking water. As a single mature larva or fertilized egg can cause infection, these should be absent from drinking water. However, the water route is relatively unimportant for helminth infection, except in the case of the guinea worm.

Legionella bacteria are ubiquitous in the environment and can proliferate at the higher temperatures experienced at times in piped drinking-water distribution systems and more commonly in hot and warm water distribution systems. Exposure to *Legionella* from drinking water is through inhalation and can be controlled through the implementation of basic water quality management measures in buildings and through the maintenance of disinfection residuals throughout the piped distribution system.

Public health concern regarding cyanobacteria relates to their potential to produce a variety of toxins, known as "cyanotoxins." In contrast to pathogenic bacteria, cyanobacteria do not proliferate within the human body after uptake; they proliferate only in the aquatic environment before intake. While the toxic peptides (e.g., microcystins) are usually contained within the cells and thus may be largely eliminated by filtration, toxic alkaloids such as cylindrospermopsin and neurotoxins are also released into the water and may break through filtration systems. Some microorganisms will grow as biofilms on surfaces in contact with water. With few exceptions, such as *Legionella*, most of these organisms do not cause illness in healthy persons, but they can cause nuisance through generation of tastes and odors or discoloration of drinking-water supplies.

Taste, odor, and appearance

Taste and odor can originate from natural inorganic and organic chemical contaminants and biological sources or processes (e.g., aquatic microorganisms), from contamination by synthetic chemicals, from corrosion, or as a result of water treatment (e.g., chlorination). Taste and odor may also develop during storage and distribution due to microbial activity.

Taste and odor in drinking water may be indicative of some form of pollution or of a malfunction during water treatment or distribution. It may therefore be an indication of the presence of potentially harmful substances. The cause should be investigated, and the appropriate health authorities should be consulted, particularly if there is a sudden or substantial change.

Color, cloudiness, particulate matter, and visible organisms may also be noticed by consumers and may create concerns about the quality and acceptability of a drinking-water supply.

Biologically derived contaminants

There are a number of diverse organisms that may have no public health significance but which are undesirable because they produce taste and odor. As well as affecting the acceptability of the water, they indicate that water treatment and/or the state of maintenance and repair of the distribution system are insufficient.

Actinomycetes and fungi

Actinomycetes and fungi can be abundant in surface water sources, including lakes and reservoirs, and they also can grow on unsuitable materials in the water supply distribution systems, such as rubber. They can give rise to geosmin, 2-methyl isoborneol, and other substances, resulting in objectionable tastes and odors in the drinking water.

Animal life

Invertebrate animals are naturally present in many water resources used as sources for the supply of drinking water and often infest shallow, open wells. Small numbers of invertebrates may also pass through water treatment works where the barriers to particulate matter are not completely effective and colonize the distribution system. Their motility may enable them and their larvae to penetrate filters at the treatment works and vents on storage reservoirs.

The types of animal concerned can be considered, for control purposes, as belonging to two groups. First, there are free-swimming organisms in the water itself or on water surfaces, such as the crustaceans (freshwater shrimp). Second, there are other animals that either move along surfaces or are anchored to them (e.g., water louse, snails, zebra mussel, other bivalve molluscs, and the bryozoan) or inhabit slimes (e.g., *Nais* spp., nematodes, and the larvae of chironomids). In warm weather, slow sand filters can sometimes discharge the larvae of gnats into the water.

Many of these animals can survive, deriving food from bacteria, algae, and protozoa in the water or present on

slimes on pipe and tank surfaces. Few, if any, water distribution systems are completely free of animals. However, the density and composition of animal populations vary widely, from heavy infestations, including readily visible species that are objectionable to consumers, to sparse occurrences of microscopic species.

Production of high-quality water, maintenance of chlorine residuals in the distribution system, and the regular cleaning of water mains by flushing or swabbing will usually control infestation.

Cyanobacteria and algae

Blooms of cyanobacteria and other algae in lakes and reservoirs and in river waters may impede coagulation and filtration, causing coloration and turbidity of water after filtration. They can also give rise to geosmin, 2-methyl isoborneol, and other chemicals, which have taste thresholds in drinking water of a few nanograms per liter. Some cyanobacterial products – cyanotoxins – are also of direct health significance.

Iron bacteria

In waters containing ferrous and manganous salts, oxidation by iron bacteria (or by exposure to air) may cause rust-colored deposits on the walls of tanks, pipes, and channels and carryover of deposits into the water.

Chemically derived contaminants

Aluminum

Naturally occurring aluminum as well as aluminum salts used as coagulants in drinking-water treatment are the most common sources of aluminum in drinking water.

Ammonia

The threshold odor concentration of ammonia at alkaline pH is approximately 1.5 mg/l, and a taste threshold of 35 mg/l has been proposed for the ammonium cation.

Chloride

High concentrations of chloride give a salty taste to water and beverages. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200–300 mg/l for sodium, potassium, and calcium chloride. Concentrations in excess of 250 mg/l are increasingly likely to be detected by taste, but some consumers may become accustomed to low levels of chloride-induced taste. No health-based guideline value is proposed for chloride in drinking water.

Chlorine

Most individuals are able to taste or smell chlorine in drinking water at concentrations well below 5 mg/l and some at levels as low as 0.3 mg/l.

Chlorophenols

Chlorophenols generally have very low taste and odor thresholds.

Color

Drinking water should ideally have no visible color. Color in drinking water is usually due to the presence of colored organic matter (primarily humic and fulvic acids) associated with the humus fraction of soil. Color is also strongly influenced by the presence of iron and other metals, either as natural impurities or as corrosion products. It may also result from the contamination of the water source with industrial effluents and may be the first indication of a hazardous situation. The source of color in a drinking-water supply should be investigated, particularly if a substantial change has taken place.

Copper

Copper in a drinking-water supply usually arises from the corrosive action of water leaching copper from copper pipes.

Dissolved oxygen

The dissolved oxygen content of water is influenced by the source, raw water temperature, treatment, and chemical or biological processes taking place in the distribution system. Depletion of dissolved oxygen in water supplies can encourage the microbial reduction of nitrate to nitrite and sulfate to sulfide. It can also cause an increase in the concentration of ferrous iron in solution, with subsequent discoloration at the tap when the water is aerated. No health-based guideline value is recommended.

Hardness

Hardness caused by calcium and magnesium is usually indicated by precipitation of soap scum and the need for excess use of soap to achieve cleaning. Public acceptability of the degree of hardness of water may vary considerably from one community to another, depending on local conditions. In particular, consumers are likely to notice changes in hardness.

The taste threshold for the calcium ion is in the range of 100–300 mg/l, depending on the associated anion, and the taste threshold for magnesium is probably lower than that for calcium. In some instances, consumers tolerate water hardness in excess of 500 mg/l.

Depending on the interaction of other factors such as pH and alkalinity, water with a hardness above approximately 200 mg/l may cause scale deposition in the treatment works, distribution system and pipework, and tanks within buildings. It will also result in excessive soap consumption and subsequent “scum” formation. On heating, hard waters form deposits of calcium carbonate scale. Soft water, with a hardness of less than 100 mg/l, may, on the other hand, have a low buffering capacity and so be more corrosive for water pipes.

Hydrogen sulfide

The taste and odor thresholds of hydrogen sulfide in water are estimated to be between 0.05 and 0.1 mg/l. The “rotten eggs” odor of hydrogen sulfide is particularly noticeable in some groundwaters and in stagnant drinking water in

the distribution system, as a result of oxygen depletion and the subsequent reduction of sulfate by bacterial activity.

Iron

Anaerobic ground water may contain ferrous iron at concentrations of up to several milligrams per liter without discoloration or turbidity in the water when directly pumped from a well. On exposure to the atmosphere, however, the ferrous iron oxidizes to ferric iron, giving an objectionable reddish-brown color to the water.

Manganese

At levels exceeding 0.1 mg/l, manganese in water supplies causes an undesirable taste in beverages and stains sanitary ware and laundry. The presence of manganese in drinking water, like that of iron, may lead to the accumulation of deposits in the distribution system.

Monochloramine

Most individuals are able to taste or smell monochloramine, generated from the reaction of chlorine with ammonia, in drinking water at concentrations well below 5 mg/l and some at levels as low as 0.3 mg/l.

pH and corrosion

Although pH usually has no direct impact on consumers, it is one of the most important operational water quality parameters. Careful attention to pH control is necessary at all stages of water treatment to ensure satisfactory water clarification and disinfection. For effective disinfection with chlorine, the pH should preferably be less than 8; however, lower-pH water is likely to be corrosive. The pH of the water entering the distribution system must be controlled to minimize the corrosion of water mains and pipes in household water systems.

Sulfate

The presence of sulfate in drinking water can cause noticeable taste, and very high levels might cause a laxative effect in unaccustomed consumers. Taste impairment varies with the nature of the associated cation; taste thresholds have been found to range from 250 mg/l for sodium sulfate to 1,000 mg/l for calcium sulfate. It is generally considered that taste impairment is minimal at levels below 250 mg/l. No health-based guideline value has been derived for sulfate.

Total dissolved solids

The palatability of water with a TDS level of less than 600 mg/l is generally considered to be good; drinking water becomes significantly and increasingly unpalatable at TDS levels greater than about 1,000 mg/l.

Turbidity

Turbidity in drinking water is caused by particulate matter that may be present from source water as a consequence of

inadequate filtration or from resuspension of sediment in the distribution system. It may also be due to the presence of inorganic particulate matter in some groundwaters or sloughing of biofilm within the distribution system. The appearance of water with a turbidity of less than 5 NTU is usually acceptable to consumers, although this may vary with local circumstances.

Temperature

Cool water is generally more palatable than warm water, and temperature will impact on the acceptability of a number of other inorganic constituents and chemical contaminants that may affect taste. High water temperature enhances the growth of microorganisms and may increase taste, odor, color, and corrosion problems.

Chemical water quality

Assessment of the adequacy of the chemical quality of drinking water relies on comparison of the results of water quality analysis with guideline values.

For additives (i.e., chemicals deriving primarily from materials and chemicals used in the production and distribution of drinking water), emphasis is placed on the direct control of the quality of these products. In controlling drinking-water additives, testing procedures typically assess the contribution of the additive to drinking water and take account of variations over time in deriving a value that can be compared with the guideline value.

Most chemicals are of concern only with long-term exposure; however, some hazardous chemicals that occur in drinking water are of concern because of effects arising from sequences of exposures over a short period. Where the concentration of the chemical of interest varies widely, even a series of analytical results may fail to fully identify and describe the public health risk (e.g., nitrate, which is associated with methemoglobinemia in bottle-fed infants). In controlling such hazards, attention must be given to both knowledge of causal factors such as fertilizer use in agriculture and trends in detected concentrations, since these will indicate whether a significant problem may arise in the future. Other hazards may arise intermittently, often associated with seasonal activity or seasonal conditions. One example is the occurrence of blooms of toxic cyanobacteria in surface water.

A *guideline value* represents the concentration of a constituent that does not exceed tolerable risk to the health of the consumer over a lifetime of consumption. Guidelines for some chemical contaminants (e.g., lead, nitrate) are set to be protective for susceptible subpopulations. These guidelines are also protective of the general population over a lifetime.

Bacterial pathogens

Most bacterial pathogens potentially transmitted by water infect the gastrointestinal tract and are excreted in the feces of infected humans and other animals. However, there are also some waterborne bacterial pathogens, such

as *Legionella*, *Burkholderia pseudomallei*, and atypical mycobacteria, that can grow in water and soil. The routes of transmission of these bacteria include inhalation and contact (bathing), with infections occurring in the respiratory tract, in skin lesions, or in the brain. A list of these is shown in the following table (Table 2).

Assessing microbial priorities

The most common and widespread health risk associated with drinking water is microbial contamination, the consequences of which mean that its control must always be of paramount importance. Priority needs to be given to improving and developing the drinking-water supplies that represent the greatest public health risk.

Water Quality for Drinking: WHO Guidelines,
Table 2 Pathogens in drinking water

Bacterial pathogens	Acinetobacter Aeromonas Bacillus Burkholderia pseudomallei Campylobacter Escherichia coli pathogenic strains Helicobacter Klebsiella Legionella Mycobacterium Pseudomonas Salmonella Shigella Staphylococcus aureus Tsukamurella Vibrio Yersinia
Viral pathogens	Adenoviruses Astroviruses Caliciviruses Hepatitis A virus Hepatitis E virus Rotaviruses and orthoreoviruses
Protozoan pathogens	Acanthamoeba Balantidium coli Cryptosporidium Cyclospora cayetanensis Entamoeba histolytica Giardia intestinalis Isospora belli Microsporidia Naegleria fowleri Toxoplasma gondii
Helminth pathogens	Dracunculus medinensis Fasciola spp.
Toxic cyanobacteria	
Indicator and index organisms	Total coliform bacteria Escherichia coli and thermotolerant and coliform bacteria Heterotrophic plate counts Intestinal enterococci Clostridium perfringens Coliphages Bacteroides fragilis phages Enteric viruses

Microbial contamination of major urban systems has the potential to cause large outbreaks of waterborne disease. Ensuring quality in such systems is therefore a priority. Nevertheless, the majority (around 80%) of the global population without access to improved drinking-water supplies reside in rural areas. Similarly, small and community supplies in most countries contribute disproportionately to overall drinking-water quality concerns. Identifying local and national priorities should take factors such as these into accounts.

Assessing chemical priorities

Not all of the chemicals with guideline values will be present in all water supplies or, indeed, all countries. If they do exist, they may not be found at all levels of concern. Conversely, some chemicals without guideline values or not addressed in the WHO guidelines may nevertheless be of legitimate local concern under special circumstances.

Only a few chemicals have been shown to cause widespread health effects in humans as a consequence of exposure through drinking water when they are present in excessive quantities. These include fluoride, arsenic, and nitrate. Human health effects have also been demonstrated in some areas associated with lead (from domestic plumbing), and there is concern because of the potential extent of exposure to selenium and uranium in some areas at concentrations of human health significance.

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Cross-references

[Cyanobacteria \(Blue-Green Algae\)](#)
[Europe, Lakes Review](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Health Aspects of Lakes and Reservoirs](#)
[Water Framework Directive](#)
[Water Quality in Lakes and Reservoirs](#)

WATER QUALITY IN LAKES AND RESERVOIRS

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Introduction

Pure water does not exist in nature. There are a wide range of factors which can be used to define water quality that no simple definition exists. Water which is of excellent quality for certain purposes may be totally unsuitable for other purposes. However, the overall quality of the aquatic environment of lakes and reservoirs can only be fully described in terms of hydrology, physicochemistry, and biology. Changes in oxygen, pH, carbon dioxide, and other variables are often substantial during a 24 h period due to the influence of solar radiation on temperature and photosynthesis. There are therefore seasonal differences in water quality due to the impact on biological

processes of differing lengths of daylight, temperature, and other factors.

Precipitation whether in the form of rain, snow, or ice washes gases and dust particles out of the atmosphere. The gases include oxygen, carbon dioxide, ammonia, and iron from industrial sources, sulfur dioxide, carbon monoxide, oxides of nitrogen, and hydrocarbons. Rainfall has always been slightly acidic due to the natural formation of carbonic acid which has become more acidic today due to the formation of nitric and sulfuric acids as a result of industrial pollution. The rain collects impurities while passing through the air and further changes in quality take place as a result of the twin processes of erosion and solution. Thus, the composition of water in lakes and reservoirs in terms of both dissolved and suspended matter closely reflects the geology of the catchment or basin. Such differences can have major influences on the aquatic flora and fauna of the catchment.

Rivers collect impurities from the earth and through the discharge of sewage and industrial effluents and these are carried to lakes and reservoirs. All surface waters must be regarded as potentially polluted although natural purification occurs in large lakes and reservoirs through sedimentation and the death of pathogenic bacteria. Water from these may frequently show no bacterial evidence of past contamination. The water quality characteristics of lakes and reservoirs are therefore variable and depend on many factors.

Storage in reservoirs

Water storage in reservoirs modifies the wide variation in water quality.

Bacterial concentrations in reservoirs are reduced as a result of the unfavorable bacteriological environment coupled with a long detention period. Turbidity is decreased by sedimentation of suspended particles in the relative quiescence of the impoundment. The bleaching action of sunlight is responsible for removing color from water retained in the reservoir. However, effects of impoundment may exhibit objectionable tastes and odors, high color, objectionable algal growth, low concentrations of dissolved oxygen, and high concentrations of iron, manganese, and hydrogen sulfide. All these, undesirable on water quality, are due largely to thermal stratification of reservoirs during certain periods of the year. Storage or residence time in lakes may range from weeks to hundreds of years.

Thermal stratification

Deep reservoirs can be expected to develop thermal stratification during the warm periods. The Spring warming of the surface waters creates thermal density differences between the deep water which has been stored through the preceding winter and the warmer low density water near the surface. This temperature gradient results in a stable stratification which resists mixing by wind and other forces.

Normally, an intermediate layer of maximum temperature gradient (the *thermocline*), forms between an upper

layer (the *epilimnion*), and the deep layer (the *hypolimnion*).

The thermocline in natural lakes is often observed in depths of 10 m or more below the surface but in reservoirs may be less depending on withdrawal rates.

Water above the thermocline in the epilimnion is stirred by wind and wave action which combines with photosynthesis of algae to maintain dissolved oxygen in the water at near saturation levels. Below the thermocline, however, little mixing occurs and sunlight, necessary for photosynthesis, does not penetrate to the hypolimnion. The stagnant water, deprived of reaeration cannot replenish the dissolved oxygen which is consumed by biochemical processes.

These processes gradually reduce the dissolved oxygen to levels significantly below saturation level and frequently exhaust it completely. The same biologically processes which utilize the oxygen, produce carbon dioxide resulting in the production of acidic conditions.

The quality of water in the hypolimnion becomes progressively worse until late summer or autumn. Cooler weather lowers the temperature of the surface water, increasing its density, so that it sinks and mixes with the deeper water in the hypolimnion. Eventually, all the water in a reservoir becomes of relatively uniform temperature and density.

In climates of warm temperature, reservoir water will remain mixed throughout its depth and well aerated during cooler periods. In cooler latitudes, however, deep reservoirs exhibit winter stratification resulting from cooling of the surface waters to below 4°C. the point of maximum density. Colder but less dense water will remain on the surface of the reservoir, with bottom water temperature at about 4°C. If ice-cover forms, wind disturbance ceases and the reservoir may become stagnant and spring will bring on warmer air temperatures and start the stratification cycle again.

Impurities in water

Impurities in water may be in solution or in suspension. Although poisonous metals such as lead may occasionally be found in natural waters, dissolved impurities are not usually harmful, but, if present in excessive quantities, they make the water undesirably hard or unsuitable for domestic and some industrial uses.

Upland reservoirs are usually of good bacterial quality on account of their situation and the protection often afforded to the gathering grounds. However in other areas, reservoirs may be affected by bacteria from excremental pollution such as types of *Escherichia coli*, *Citrobacter freundii*, *Klebsiella aerogenes*, and *E. cloacae* (*Enterobacter cloacae*).

Diseases of bacterial origin

Diseases of bacterial origin associated with water from reservoirs if not satisfactorily treated are:

1. Typhoid
2. Paratyphoid

3. Cholera
4. Dysentery (bacillary and amoebic)
5. Gastroenteritis
6. Weil's disease (Leptospirosis jaundice)

Measurement of water quality in lakes and reservoirs

Temperature

Temperature is a key characteristic of all water bodies because it influences physical, chemical, and biological processes. Lakes and reservoirs exhibit both seasonal and diurnal variations in temperature which may be related to climate and geographic location. Shallow lakes may have a uniform temperature from top to bottom, but deep lakes may become stratified.

Temperature is always measured in situ at the time of sampling by means of a thermometer or thermistor.

Transparency

Transparency is a useful guide to biological productivity and is measured in the field usually from a boat by lowering a white circular disk 200 to 300 mm in diameter (known as a Secchi disk) on a graduated cable and observing the depth at which it disappears from sight. It is then slowly raised and the depth at which it reappears is noted. The mean of these two depths is the depth of transparency.

The transparency of natural waters can vary substantially in Europe usually from 0.5 to 15 m, but values of 50 m have been observed in some crater lakes and values of 20–25 m have been observed in European alpine lakes.

Color

The true color of a sample of lake water can only be measured in the laboratory after filtration. The true color is measured after filtration either visually or by a photoelectric method.

Turbidity

Turbidity in lakes arises from the scattering of light by suspended solids. Turbidity measurements are of particular interest to managers of water treatment works as a quick and simple guide to water quality.

Suspended solids

Almost all surface waters contain suspended particulate matter which is derived from natural weathering in the catchment.

Suspended solids by settling out on the lake or reservoir bed can be harmful to bottom living organisms and prevent the breeding of fish by stopping the free flow of oxygenated water through the gravel in which the fish lay their eggs. Total suspended solids (TSS) are determined in the laboratory by passing the water sample through a special filter. TSS is one of the most variable of water quality characteristics.

Total dissolved solids

Total dissolved solids (TDS) are determined by passing a measured volume of the sample through a filter of small pore size and evaporating the filtrate in an evaporating dish.

Conductivity

Electrical conductivity provides a simple way of estimating the concentration of dissolved organic salts. The method is particularly useful in reservoirs of potential sources of drinking water. The test is best carried out in the field using a conductivity meter. It is measured in Siemens per meter or in millisiemens per meter. The values found in most natural lakes are in the range 5–50 mS/m but may rise to 100 or more in mineralized waters and in very polluted waters could rise to 1,000 mS/m.

pH

The pH scale is a convenient way of measuring the acidity or alkalinity of a sample of lake water. The scale extends from 0 (extremely acid) to 14 (extremely alkaline), while the midpoint pH7 corresponds to exact neutrality. In natural lake water, pH is controlled by the relationship, or equilibrium, among carbon dioxide, bicarbonate, and carbonate ions, and can be strongly influenced by biological activity. Thus, photosynthesis by algae and other plants during daylight hours utilizes carbon dioxide and the pH may rise sharply, while by night the main biological activity is respiration which produces carbon dioxide and the pH decreases accordingly.

The natural pH of rain is around 5.6, but industrial emissions of sulfur dioxide together with oxides of nitrogen from industry and transport lead to the formation of sulfuric and nitric acids so that rainfall has become much more acid during the last century average values ranging from 4 to 5 in Europe. Some waters are naturally acidic in mountain areas due to humic acids, but not as acidic as those affected by industrial acidification. In some circumstances in lakes a total loss of fish life can occur.

Chemical characteristics

The chemical components of natural waters in lakes can be grouped in five categories: particulate; inorganic substances; dissolved inorganic substances, and dissolved gases.

Particulate inorganic substances, the main source of minerals which carried in suspension by streams in the catchment, are the mechanical erosion of rocks and soils brought about by wind, running water, frost, ice movement, and land slips. In lakes, particulate matter is also derived from biochemical processes such as photosynthesis which cause the precipitation of calcium from solution as calcite (calcium carbonate).

Dissolved inorganic substances

As soon as rain falls on the earth's surface, it starts to dissolve minerals according to the acidity or alkalinity of the water, the relative solubilities of the minerals and other factors.

Rainwater contains many ions in solution, and of these sodium, potassium, calcium, magnesium, and chloride are derived mainly from particles in the atmosphere, while sulfate, ammonium, and nitrate ions are derived mainly from atmospheric gases. It is estimated that about 54% of the rain falling on the earth's surface is evaporated, leaving 46% as runoff so that the concentration of ions in river water is over double that derived from rainwater. Most of the dissolved inorganic material in rivers and lakes originates from the weathering of rocks and soil and from man-made sources. It is estimated that in some countries 10–15% of calcium, sodium, and chloride comes from rainfall in contrast to about one quarter of the potassium and half of the sulfate.

Major ions

Sodium

Sodium is one of the most abundant elements in the earth's crust and is present in all natural waters. In surface water the natural concentrations is usually below 10 mg/l and rarely above 50 mg/l. Analysis is normally carried out by atomic emission spectrophotometry.

Potassium

Concentration of potassium is generally low in lakes except in agricultural areas where fertilizers may give high levels. Analysis is carried out by atomic emission spectrophotometry.

Calcium

Calcium is widely distributed in surface rocks, usually in the form of carbonate or sulfate, for example, limestone chalk and gypsum. Natural lake water usually contains less than 15 mg/l.

Calcium and magnesium which are invariably present together are responsible for hardness in water which can be defined as the ability of the water to precipitate calcium and magnesium salts of fatty acids from soap solution. Analysis is by titration with ethylenediamine (EDTA).

Magnesium

Magnesium is an essential element for living organisms and universally present in natural waters. Concentrations in lake water are usually in the range 1–100 mg/l.

Analysis is by titration with EDTA or by atomic absorption spectrophotometry.

Carbonates and bicarbonates

All natural waters contain in solution carbon dioxide, carbonic acid, carbonate, and bicarbonate ions in a buffered system which is important to the health of the aquatic flora and fauna. Carbon dioxide is derived from the atmosphere by absorption at the air–water interface from the respiration of aquatic organisms and from the bacterial decomposition of organic matter either in suspension or in the bottom sediments. The weathering of rocks contributes carbonate and bicarbonate salts. In areas of non-carbonate

geology, the carbonate, and bicarbonate is entirely derived from the atmosphere and biogenic carbon dioxide.

Photosynthesis plays a major role in the precipitation of calcium carbonate in lakes and in very pure waters the results of acid rain may seriously depress the pH to 4.5 or less resulting in the death of fish eggs and fry. The deaths may not be directly caused by the acidity but by toxic metal aluminum leached from the soil under acid conditions.

Concentrations of carbonate, bicarbonate, and carbon dioxide are usually calculated from measurements of the pH (by glass electrode), alkalinity (by titration), temperature, and ionic strength.

Sulfate

Sulfate is highly soluble and widely distributed in surface rocks and easily leached from gypsum (calcium sulfate). Levels in lakes may have concentrations in the range 1–80 mg/l although pollution from industrial sources may result in much higher levels. Natural hot spring waters may contain several thousand mg/l.

Analysis may be carried out by gravimetric determination of barium sulfate after ignition or by EGTA titration.

Chloride

Chloride is universally present in freshwaters derived from weathering of sedimentary rocks and rain. The average concentration in rivers and lakes may be under 10 mg/l, but high levels can occur due to pollution or industrial inputs. Lakes in coastal areas may have very high concentrations. Chloride is chemically and biologically unreactive and samples may be stored at room temperature. Analysis is by titration with silver nitrate or directly with chloride sensitive electrodes.

Minor ions

Minor ions: nitrate, phosphate, and silicate are of vital importance in aquatic ecosystems as nutrients for plant growth and particularly in the growth of phytoplankton and may limit productivity at low concentrations while high levels may cause undesirably high growths of macrophytic plants and algae.

Nitrogen

Nitrogen is essential for all living organisms as a major constituent of protein and genetic material such as DNA. Bacteria and plants utilize inorganic nitrogen from the water to produce organic matter such as protein within their cells while animals such as zooplankton and fish derive their protein from plants. When these organisms die, a range of microorganisms convert organic compounds, such as the various proteins, to ammonia and eventually to gaseous nitrous oxide and elemental nitrogen. These transformations form part of the nitrogen cycle found in terrestrial eco-systems.

In lakes nitrogen is present as nitrate at concentrations of about 0.1 mg/l as nitrate nitrogen. Levels of ammonia and of nitrite are usually below 0.1 mg/l because nitrifying bacteria ensure that any residue is oxidized to nitrate.

Phosphorus

Like nitrogen, phosphorus is an essential element for plant growth, being a constituent of protein, phospholipids, and nucleic acids. It is present in lakes in the form of orthophosphate, polyphosphate, and organically bound phosphates. In lakes phosphorus is normally found in the range from 0.005 to 0.02 mg/l but may be much higher if pollution is present. Analysis is by filtration. Results are reported in terms of phosphate phosphorus.

Silicate

After oxygen, silicon is the most abundant element in the earth's crust and a major constituent of igneous and metamorphic rocks, clays, feldspars, and quartz. It is believed that dissolved silica in lakes is derived from the chemical weathering of aluminum silicates by complex processes. The measurement is usually by as the oxide, silica, the concentration lying between 1 and 30 mg/l but may be as much as 1,000 mg/l in brackish lakes.

Analysis is by the calorimetric method using plastic containers to prevent leaching of silicate from glass.

Trace inorganics

The trace metals found almost universally in lakes are: iron, copper, cobalt, boron, manganese, molybdenum, zinc and aluminum. These are important as micronutrients with concentrations of between one nanogram and one microgram per liter.

Chemical analysis at these levels requires specialized trained staff with absorption spectrometry and electrothermal atomization or other instrumentation.

Particulate organic substances

Particulate organic matter in lakes includes living microscopic organisms such as phytoplankton, zooplankton, and bacteria, dead organisms, breakdown material of decaying leaves and large animals, windblown pollen and seeds. Particulate organic matter is measured as particulate organic carbon (POC) by a variety of methods, all of which are based on the oxidation of the carbon in the sample after filtration and drying to carbon dioxide. The oxidation is performed by combustion and the carbon dioxide produced measured using a specific electrode or other means.

Dissolved organic substances

These are derived from the breakdown of solid organic matter by natural biological processes some of which may take place within the lake and are measured as dissolved organic carbon (DOC).

In most lakes DOC comprises the greater part of the total organic carbon and is in the range 1–20 mg/l. Total organic carbon (TOC) is determined without filtration.

Gases in solution

Oxygen and nitrogen dissolve in water in different proportions from those in the atmosphere. However because it is chemically inert, nitrogen is not important in water quality

in lakes. In water quality aspects, the important gases are therefore oxygen and carbon dioxide. Oxygen is vital to all living organisms and because only small amounts are present in water even under saturated conditions, the concentration of dissolved oxygen is a key measure of the health of lake water. In lakes, dissolved oxygen can show marked diurnal and seasonal variation especially under eutrophic conditions. In strong sunlight in summer, the surface layers of lakes may become supersaturated with oxygen concentrations of 150–200%, while during darkness, respiration of the plankton may reduce the dissolved oxygen to saturation values of 50–80%. In extremely eutrophic lakes especially with pollution present, the dissolved oxygen concentrations may decrease to near zero, thus causing fish deaths.

Carbon dioxide

While air contains about 21% oxygen and only about 0.03% carbon dioxide, the higher solubility of the latter means that its relative concentration in water is proportionally higher. Since carbon dioxide reacts with water to produce carbonic acid, the equilibrium between the various components is highly complex.

In eutrophic lakes with abundant phytoplankton, photosynthesis in daylight depresses the carbon dioxide while oxygen is substantially increased and because of its relationship with carbon dioxide, the pH can rise significantly. The reverse takes place at night when carbon dioxide increases, the pH drops, and oxygen decreases.

Hardness

Hardness is the term used in the water industry for describing the suitability of water for domestic and industrial purposes. Hard water contains high concentrations of calcium and magnesium salts such as bicarbonates, sulfates and chlorides which are precipitated from solution by soap and by heating. Natural hard waters are typically found in areas of calcareous sedimentary rocks such as chalk and limestone while soft waters occur in areas of basic or metamorphic rocks such as granite and slates. Hardness is of importance in that it influences the toxicity of many heavy metals such as copper and lead to aquatic organisms but otherwise is not a particularly useful term for describing the quality of waters in lakes.

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[Acidification in Lakes](#)
[Carbon Cycle in Lakes](#)
[Cyanobacteria \(Blue-Green Algae\)](#)
[Eutrophication in Fresh Waters: An International Review](#)
[Health Aspects of Lakes and Reservoirs](#)
[Nutrient Balance, Light, and Primary Production](#)
[Reservoir Sedimentation](#)
[Sedimentation Processes in Lakes](#)
[Water Framework Directive](#)
[Water Quality for Drinking: WHO Guidelines](#)

WETLAND AREAS AND LAKES IN BULGARIA

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Introduction

“Wetland areas” as an independent category of natural water sites are very often omitted in the formulation of the subject of hydrological activities. These areas comprise lakes and marshes, water reservoirs of total depth below 6 m, coastal strips, and other sites of stagnant water or high humidity level.

Definition of wetland areas

These areas have characteristics, which have not been adequately studied by the contemporary environmental science since it would require the combined efforts of specialists from different research fields, including ecology, chemistry, hydrology, engineering sciences, economic sciences, etc. For this reason, the different specialists deal with different definitions, which is a natural outcome of the fields of their specific interests and research methodology.

Wetland areas are part of the natural environment characterized by permanent presence of water. The influence of the water cycle on the wetland areas is most often connected with changes in their water regime during the different hydrologic seasons. They are multifunctional sites, which provide very often human settlements with drinking water and water for industrial applications, serve as locations for angling and sources for irrigation purposes, act as buffers against floods and as tailing reservoirs for urban and industrial wastewater, serve as transport ways or sources for power generation, and, last but not least, they are indispensable for wild life and plants. Sometimes, they are called “nature’s kidneys” because of their function in the hydrological and chemical cycle. They clean contaminated waters. They feed the ground water-bearing layers. They are also often called “biological supermarkets” because of the rich biodiversity available in them.

Different professionals – geologists, soil scientists, hydrologists, biologists, ecologists, sociologists, economists, specialists in political sciences, medical doctors, and jurists give different definitions, which is a natural

consequence of their different spheres of interest, the educational background of the providers of the definition and the different way in which they treat these areas. They rank among the most significant ecosystems on the Earth and are a valuable source, host and transformer of a great multitude of chemical, biological, and genetic materials. Many of them produce large quantities of their own organic matter, which may have a strong impact on water quality by changing even its color or increasing the value of the chemically required oxygen (CRO). Maltby et al. (1998) systematize the functions and impacts of wetland areas on other spheres of natural environment and society, thus highlighting their great importance for science and the social practice.

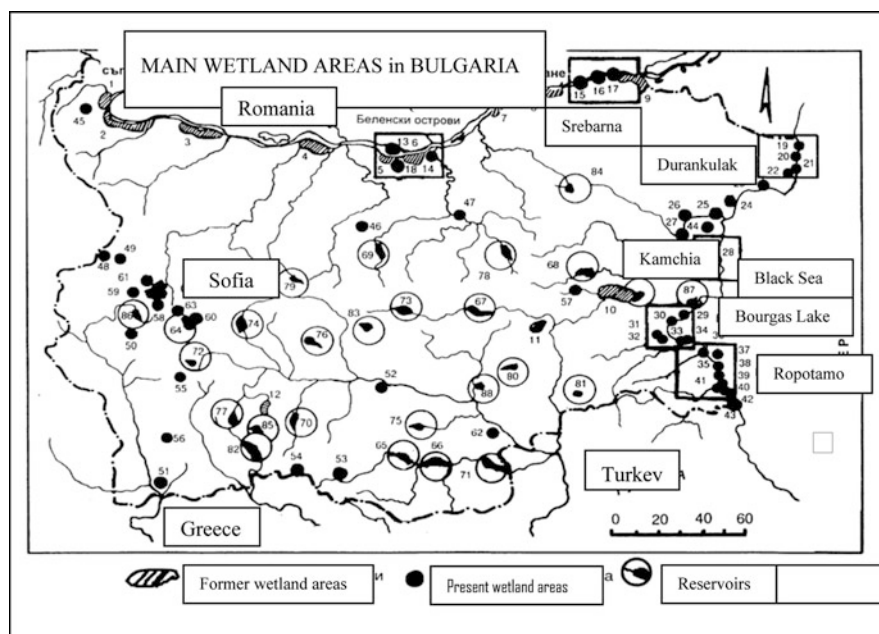
From the conducted study of literature sources, it has become evident that there is no satisfactory and generally recognized definition of the natural sites known under the name “wetland areas.” The definition that enjoys the broadest popularity is that of the Ramsar Convention (Ramsar Convention on Wetlands, 1990) concerning wetland areas of international significance. According to it, wetland areas are natural sites, which comprise “swamps, peat-bogs and natural or manmade, permanent or temporary water areas of static or running fresh, slightly salty and salty water, including areas filled by sea water, whose ebbing depth is below 6 m.”

Natural wetland areas

At the beginning of the twentieth century in Bulgaria, there were 200,000 ha of natural lakes and marshes. The first large-scale efforts for reclamation of marshland areas were launched in the 1920s with the Straldga Marshland. From a modern environmental point of view it is, however, a rough assault on the largest and one of the richest marshlands in Bulgaria. Afterward, the appetites turned to the next biggest swamp – the Karaboaz Marshland, drained by the end of the 1930s. The objective was to allot the land reclaimed from nature as arable land to emigrants from Aegean Thracia and Asia Minor. Interventions of this kind used to be conducted during the same period in the river Sruma and river Mesta estuaries in Greece, which indicates that reclamation used to be a mass practice in some European countries in the early twentieth century.

In the sense of that above formulation, a large number of wetland areas had existed in Bulgaria by the end of World War II – marshlands along the low-lying banks of the river Danube, along the stretches of many tributaries of the Danube River in the Black Sea coastal area and in the Thacian Lowlands. Illustrated on [Figure 1](#) is a scheme of the distribution of the significant natural and technogenic wetland areas in the country (Report..., 2000).

After World War II the liquidation of marches, above all along the Danube River banks, acquired mass scale with the motivation to combat mosquitoes and malaria, as well as to reclaim new arable land, which had been distributed among the poor inhabitants for tilling.



Wetland Areas and Lakes in Bulgaria, Figure 1 Scheme of the distribution of natural and man-made wetland areas in Bulgaria.

Within a brief period of time almost all marshes along the Danube River, with the exception of Srebarna, Malak Preslavets, and Garvan, had been drained (refer to Table 1).

The Mandreshko Lake and Rabishko Lake have been converted into reservoirs by dams. The same fate has befallen the Batak Marshland in the Rhodopes Mountains after the construction of a large dam on its location. At the same time, embankments and riverbed correction facilities have been built along the stretches of the feeder river to prevent the overflow of its water over its banks. In this way within short time, the desired positive drainage effect has been achieved, accompanied by lasting changes in the topography of the locality, the vegetation cover of the affected areas, and the local ecology. The drainage facilities have ensured retention of the high runoff waves and their accumulation for the purposes of irrigation and combating floods (Gergov, 1963). These interventions have, however, destructed the routes for natural supply of the wetland areas with nutrient substances and river sediments, which endangers their existence. The larger wetland areas in still active state in Bulgaria are listed in Table 2.

River training works have been made, which have destructed almost all the existing meanders. As a result only a small portion of the natural wetland areas has been preserved in Bulgaria, whereas almost all of them have been influenced by human activities.

The study and preservation of wetland areas in Bulgaria has started at the beginning of the last century with a detailed description of the vegetation and animal species in the Straldga Marshland (Yokimov, 1909). Another

Wetland Areas and Lakes in Bulgaria, Table 1 Drained marshes

1	At the city of Vidin
2	Archar – Lom Lowlands
3	Kozloduy Lowlands
4	Karaboaz Lowlands
5	Belene marshland
6	Svishtov Marshland
7	Martenska Lowlands
8	Babovo, Nova Cherna, Brashlyan, Tutrakan
9	Vetreno, Aydemir, Silistra
10	Straldga Marshland
11	Kershensko Marshland
12	Batashko Marshland

study of this kind on vegetation in marshes was conducted by Yordanov (1931). Striburni (1930) has described the Karaboaz Marshland and Petrov (1961) – the Srebarna Lake. An in-depth survey of the wetland areas in Bulgaria was made by Kochev and Yordanov (1981). A complete literary survey and detailed study of the algae-flora of the Bulgarian Danubean coastline and the adjacent basins have been conducted by Draganov and Staneva (1992), of the zoo-plankton – by Naydenov (1984) etc. Ivanov et al., (1961) have compiled a complete hydrographic directory and hydrological description of natural lakes in Bulgaria by means of maps, schemes, sectional views, and other forms of useful information. This publication contains part of the collected information about the quality of water there, the zoobenthos, biocenosis, aqua species, and other

Wetland Areas and Lakes in Bulgaria, Table 2 Existing natural lakes and marshlands

1	On Belene Island
2	On Vardim Island
3	Malak Preslavets
4	Garvansko Marshland
5	Srebarna
6	The Kaykusha Marshland (to the south of the city of Belene)
7	Durankulak Lake
8	Shabla Lake
9	Shablenska Tuzla
10	Nanevska Tuzla
11	Balchishka Tuzla
12	The river Batova mouth
13	Varna Lake
14	Beloslav Lake
15	Synedelsko Marshland
16	The river Kamchiya mouth
17	Pomoriysko Lake
18	Atanasovsko Lak
19	Bourgas Lake
20	Mandrensko Lake
21	The "Poda" Locality
22	Chinhene Skele
23	Uzun Geren
24	Alepu
25	Arkutino
26	The river Ropotamo mouth
27	Stanoplo
28	Dyavolsko Marshland
29	The river Karaach mouth
30	The river Veleka mouth
31	The river Silistrar mouth
32	Yaltata Locality (to the south of Beloslav)
33	Rabishko Lake
34	Devetashki Lakes
35	Dgulyun Gyol at the village of Draganovo
36	Dragomansko Marshland
37	Aldomirsko Marshland
38	Cholyovo Marshland
39	Marshland areas near the village of Marikostino
40	Martvitsata near the village of Popovitsa
41	Smolyan Lakes
42	Trigrad Lakes
43	Rila Lakes
44	Pirin Lakes
45	Skalensko Marshland
46	Boyana Marshland areas (near Sofia)
47	Dragichavski Marshland
48	The marshland areas of Lozen Mountains
49	The marshland areas of Lyulin Mountains
50	Sazluka Marshland near the village of Bisser
51	Kazichene Marshland

ecosystems, as well as the issues related to their conservation as nature sites.

The existent currents and pollution of the Bourgas Bay have been detected by means of two detailed nature "snapshots" taken in the course of two consecutive expeditions conducted in 1986 and 1988 (Gergov et al., 1990), immediately after the Chernobyl incident. During calm, anticyclone weather, cyclone-type circulation current has been

detected (Figure 2), extending over the entire aquifer of the Bourgas Bay and causing long-lasting retention (up to 18 days) of pollution generated by the city of Bourgas and its industrial zone. This phenomenon causes deterioration of the quality characteristics of the beaches and presents a potential health risk for the holiday-makers in this area. The speed of the currents is quite low – up to 15–16 cm/s.

Their existence has been corroborated through analysis of satellite photos of the area and through conducting of densitometric analysis (Mishev et al., 1982). Reference to other investigations of this kind is made in an article devoted to the currents in the area of the hydrological complex Varna Bay – adjacent lakes (Vesselinov and Gergov, 1980).

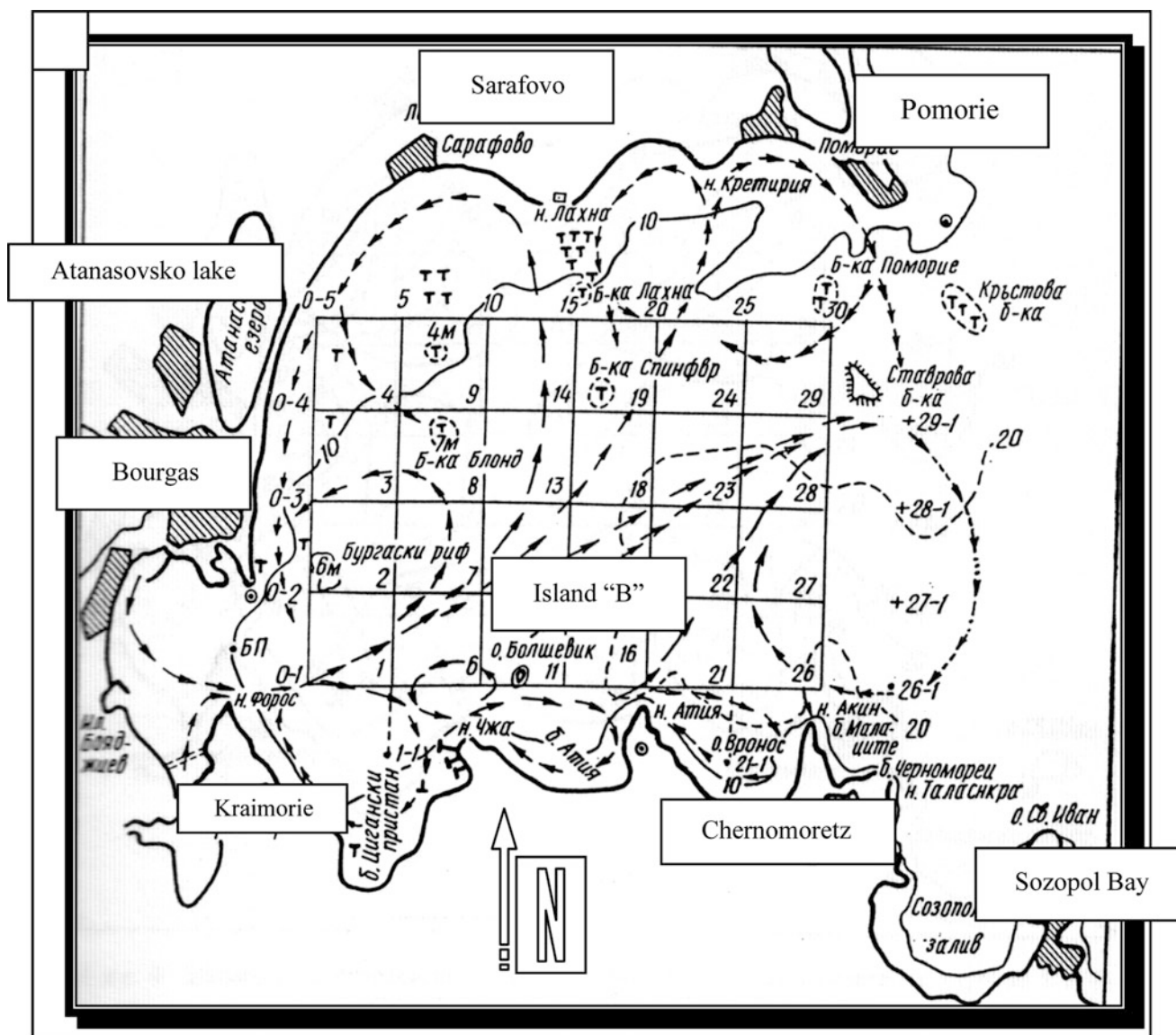
The first natural wetland area placed under the protection of the Law on Nature Protection was the river Ropotamo, declared in 1940 as a nature reserve. Proposals for two more natural wetland areas – the Srebarna and Arkutino reserves – were put forward together with the document for incorporation of the Ropotamo nature reserve in the list of sites covered by the Convention on Wetland Areas. In 1984, two more reserves were added to the list of Bulgarian sites – Atanasovsko Lake and the Durankulak Nature Landmark. The four sites account for a total area of 2,097 ha. Bulgaria joined also the Regina Convention of 1987 by virtue of Decision No. 76/1990 of the Bureau of the Council of Ministers and in this way the state began to fulfill its financial and protection-related obligations ensuing from it. In connection with the implementation of the Convention in 1994, a new integrated National Plan concerning priority actions for conservation of the 88 most significant wetland areas was developed. This plan distinguishes between three groups of wetland areas.

- Drained marshes – 12
- Existing lakes and marches in natural condition – 51
- Dams – 22

Listed in Table 3 are the priority natural wetland areas according to the National Plan, divided into three groups: wetland areas of global significance, wetland areas of continental significance, and wetland areas of national significance.

Man-made wetland areas

For the purposes of this study, a review is made of the category on man-made wetland areas such as artificially created ground pits, filled permanently or temporarily with stagnant water, irrespective of the depth of the water layer up to maximum 6 m. The lifting of this limitation as to the water depth allows us to extend the coverage of the studies to all the dams and micro-dams constructed in the country. Moreover, the areas along the banks of the big dams have all the features and characteristics of wetland areas – small depth, slow currents, higher temperature of the water environment, contacts with polluters, and other agents of anthropogenic origin. They contribute to regulation of



Wetland Areas and Lakes in Bulgaria, Figure 2 Currents in the aquifer of the Bourgas Bay in anti-cyclone weather (Gergov et al., 1990).

defused pollution coming from the neighboring agricultural areas, deposition of sediment matter, transformation of the biogenic elements and their biological, photochemical, and mechanical disintegration, reduction of soil erosion, and under certain circumstances prevention of flooding of the areas situated at lower levels. The existence of dams enriches the landscape, creates new conditions for recreation, sports, and business activities, and contributes to the development of natural habitat for many plant and animal species. In the literature, these kind of artificial lakes are generally called “man-made wetland areas” (Yokimov, 1909). The man-made wetland areas are particularly important for the maintenance of the water

ecosystems, for improvement of the quality of water through self-purification, etc.

Regretfully, however, the operation and protection of this kind of wetland areas are not clearly regulated in the national legislation and in the European directives concerning water and water facilities. There exist a relatively small number of rules and legally established standards and documents related to their implementation.

The majority of the smaller dams (approx. 2,000) are multifunctional, used mainly for irrigation, as fish-breeding and recreation facilities, while the bigger dams ($>10.10^6 \text{ m}^3$) are used mainly for energy generation and water supply.

Wetland Areas and Lakes in Bulgaria, Table 3 Priority natural wetland areas in Bulgaria

1	<i>Wetland areas of global significance</i>
1.1	Srebarna Lake
1.2	Durankulak – Shabla
1.3	Bourgas lakes
2	<i>Wetland areas of continental significance</i>
2.1	Ropotamo Reserve
2.2	Belene Island
2.3	Vardim Island
2.4	Kamchiya Reserve
3	<i>Wetland areas of national significance</i>
3.1	Pomoriysko Lake
3.2	River Veleka mouth and River Silistar mouth
3.3	the marshland at the village of Malak Preslavets
3.4	Garvansko Marshland

To insure good functioning the dams require protection of their internal hydrological system and water circulation, which are often distorted or neglected because of the insufficient or entirely missing knowledge about their management on part of their owners. The period of transition of Bulgarian agriculture through privatization has had a grave impact on many water sites because of the failure of the state to set up a regulatory framework for their safe and environmentally sound operation, maintenance, and protection.

Dams in Bulgaria

A total of 2,040 dams with a summary storage capacity of 7.773 billion cubic meters (refer to Table 4) are in situ in the country for regulation of the seasonal and multi-annual water runoff. The degree of runoff regulation achieved in this way is about 39%, ensuring approximately 920 m³/inhabitant. Their major hydrographic and water economy characteristics are systematized in several publications (Nikolova, 2000; Report, 2000; Gergov and Varbanov, 2002).

The experience accumulated in Bulgaria has revealed that dams with a storage capacity above five million cubic meters (a total of 91 with a summary storage capacity amounting to 7.036 billion cubic meters or 90.5% of the total installed storage capacity of all reservoirs) have a great importance for development of water economy activities and for meeting the water demands of the country. The remaining 1,949 dams feature storage capacity below five million cubic meters and are predominantly of local importance and therefore do not play a decisive role for the sustainability of the national water economy balance.

Aerial distribution of the dams in terms of their storage capacity

The aerial distribution of this type of wetland areas is of great significance for meeting the demand of drinking water and water for other different applications, like irrigation and power generation. Bulgarian rivers are not

Wetland Areas and Lakes in Bulgaria, Table 4 List of complex and significant dams

1	A. Stamboliyski
2	Assenovets
3	Aheloy
4	Batak
5	Beglika
6	Beli Lom
7	Belmeken
8	Borovitsa
9	Vacha
10	Georgui Traykov
11	Golyam Beglik
12	Gorni Dabnik
13	Domlyan
14	Dospat
15	Dyakovo
16	Enitsa
17	Zhrebchevo
18	Ivaylovgrad
19	Iskar
20	Yovkovtsi
21	Kalin
22	Kamchiya
23	Karagyo
24	Kokalyane
25	Koprinka
26	Krichim
27	Kula
28	Kardgali
29	Malko Sharkovo
30	Ognyanovo
31	Ogosta
32	Pancharevo
33	Poroy
34	Pchelina
35	Pyasachnik
36	Rabisha
37	Rozov Kladenets
38	Sopot
39	Srechenska Bara
40	Studen Kladenets
41	Studena
42	Saedinenie
43	Ticha
44	Topolnitsa
45	Toshkov Chark
46	Trakiets
47	Hristo Smimenski
48	Chaira
49	Shiroka Polyana
50	Yasna Polyana
51	Yastrebino

navigable because of their variable hydrological regime. There exist, however, certain preserved memoirs and monastery chronics, which tell that till the end of the Middle Ages cargo barges and rafts used to sail along the lower stretches of the rivers Struma, Maritsa, and Iskar, carrying, timber goods and livestock from the inland to the Arabian markets. This information may be assumed as evidence for the high water-bearing capacity of the

region, formed by the climate during that period, and the overall spread of natural forest areas.

The dams for irrigation purposes enjoy the broadest distribution. The majority of them are situated along the river courses as follows: along the Maritsa River – about 665, Tundga – 245, Yantra – 181, Kamchiya – 121, etc. The largest number of big dams (storage capacity above five million cubic meters) exists along the courses of the Maritsa River (24), Kamchiya (9), Struma and Yantra (7 each), Iskar (6) and Tundga (5).

The constructed dams allow high degree of regulation of the river discharges thanks to their available storage capacities. For the main rivers in Bulgaria, these are as follows: river Maritsa – 1.599 billion cubic meters, river Arda – 1.269 billion cubic meters, river Kamchiya – 0.978 billion cubic meters, river Iskar – 0.814 billion cubic meters, and river Ogosta – 0.585 billion cubic meters. The dam storage capacities in situ along the border rivers (Nishava, Erma, Veleka) and some of the rivers discharging in the Black Sea (Devnya, Dvoynitsa, Fakiyska etc.) are insignificant. Their small annual runoff might be subjected to higher degree of regulation through construction of small dams or redistribution of their runoff across the area.

Distribution of dams in terms of designation

According to their designation the dams may be divided into the following groups:

- Dams of complex designation
- Dams for irrigation purposes
- Dams for energy generation
- Dams for drinking water supply
- Dams for industrial water supply
- Dams for fish-breeding
- Retention storage capacities and dams of special designation

The complex dams belong to the sites of national significance and for that reason their management involves more complicated principles of subordination – neither sector-based alone, nor territorial alone. There are a total of 30 such dams, featuring total storage capacity of 3.1 billion cubic meters (Table 4), which accounts for 40% of the summary installed storage capacity in the country. These dams are of exclusive importance for meeting the drinking water demand. Their share is the biggest along the river Maritsa (the so-called Rila-Rhodopes cascades), comprising five complex dams of 0.67 billion cubic meters total storage capacity, followed by that along the river Iskar – four dams, total storage capacity 0.54 billion cubic meters and the river Ogosta – three dams, storage capacity 0.51 billion cubic meters.

The total storage capacity of regulated water, which is used for *irrigation* purposes, is about two billion cubic meters (25% of the total capacity). The largest number of dams for irrigation purposes exists along the river valleys possessing favorable conditions for agricultural irrigation.

- River Maritsa 650 dams with a total storage capacity 0.714 billion cubic meters
- River Tundga 242 dams with a total storage capacity 0.15 billion cubic meters
- River Yantra 161 dams with a total storage capacity 0.144 billion cubic meters
- River Kamchiya 113 dams with a total storage capacity 0.414 billion cubic meters
- River Vit 58 dams with a total storage capacity 0.105 billion cubic meters

The small dams (below five million cubic meters) have multiple applications in agriculture – for irrigation, stock-rearing, fish-breeding, etc. – at relatively low costs and minimum maintenance requirements. Unfortunately, the construction of the reservoirs had not been based on adequate design, construction methods, and maintenance provisions, specific for that type of facilities (Stoychev et al., 1988). On the other hand, these are small facilities, which do not require any particular care and maintenance during their short life cycle. The use of local materials for their construction gives their users the self-confidence that this is light and insignificant construction effort.

Mass distribution has been noted for *micro-dams* (below one million cubic meters storage capacity), which are spread all over the country. Some of them have been converted into recreation areas. Almost all of them have been constructed with funding allocated by the Ministry of Agriculture from the Regional Territorial Development Fund or Mitigation of Erosion Fund, however at the national level there is no summary information about them at all.

There is a total of ten water supply dams with a total storage capacity of about 0.5 billion cubic meters, the biggest ones being those on the rivers Yantra, Kamchiya, and Iskar.

The number of dams used specifically for *power generation* is small – a total of nine with a total storage capacity of 1.173 billion cubic meters, which account for approximately 15% of the total storage capacity of dams in the Republic of Bulgaria. Their regulation capacity is considerable. A number of dams, which have originally been built for power generation, have later shifted to the group of complex ones, since the development of the area had put forward the requirement for priority meeting of other types of water demand. In perspective there are no plans for construction of dams specifically for power generation with the exception of the Gorna Arda Cascade. Famous big dams for power generation applications in the country are Iskar, the Batak Cascade, Vacha Cascade, Topolnitsa, Koprinka, Al. Stamboliyski, Petrokhan etc.

Dams for water supply applications are in situ at many places throughout the country. The better known among them are Yasna Polyana, Hristo Smirnovski, Tsonevo, Srechenska Bara, Beli Iskar, Dyakovo, etc. The dams for industrial water supply with conventionally clean water are also only a few (14) and of insignificant storage capacities – 0.294 billion cubic meters or 4.4% of the total volume of the water reservoirs.

There are about 20 water reservoirs for fish breeding in situ in the country. Their storage capacity is insignificant – 0.4% of the total. There are also 21 dams for struggle against floods (retention capacities) and special purpose dams, whose storage capacity is also insignificant (0.2% of the total). In recent years, as a consequence of the transfer of the small irrigation dams under the control of municipalities, or their privatization, or yet their lending for operation and management under concession agreements, they are used predominantly for fish breeding.

The fish-breeding ponds are usually built on the location of former lakes, marshes, and quagmires, some of the more famous among them being those at the village of Orsoya, the village of Mechka, the village of Nova Cherna, the village of Karaysen (Veliko Tarnovo District), the city of Byala, the city of Rousse, the village of Chelopechene, Sokolitsa, the city of Blagoevgrad, the city of Plovdiv, etc.

Quarry lakes have been formed as a consequence of the extraction of clay, gravel, sand, or coal. They are used most frequently as retention storage capacities for irrigation, water supply for agriculture, stock-rearing, etc. These are some of the water facilities, which have a variety of negative impacts on the environment (Yurdanov and Gergov, 1996).

Rice fields occupy relatively vast areas around the cities of Pazardgik, Plovdiv, and Stara Zagora. Their intensive cultivation is connected with increased impact on the water resources and the environment in these regions.

The period before the passing of the Law on Local Self-government and Local Administration, at the offset of the economic reforms in the Republic of Bulgaria, was characterized by two types of ownership on the dams: state and cooperative. Cooperative ownership extended over 1,847 dams of summary storage capacity of 0.533 billion cubic meters. State ownership is split and comprises 166 hydro-ameliorative and complex dams of a total storage capacity of 2.527 billion cubic meters.

After the promulgation of the Law on Local Self-government and Local Administration, a process of transformation of the ownership on the small dams had started. However, sometimes after its enforcement the launching of the agrarian reform triggered a new problem the absence of criteria for identification of the ownership rights on them and the inadequacy in their management, which might lead to their ruins.

These are engineering facilities implemented by means of local building materials, without adequate technical supervision of their state and operation (Stoychev et al., 1988). They meet local needs, such as irrigation of vegetable gardens, fish-breeding, stock-rearing farms, sports, and entertainment. In certain cases, they feed water to small irrigation-bound fields. The design of the small dams has been made practically in the absence of reliable hydrological data because there were no hydrometric stations installed on the brooklets and small rivers. For this reason, empirical data and improper methodologies were usually used for that purpose and consequently these

facilities bear the risk of unforeseen averages in the event of formation of torrential floods. There is no information with respect to the sediment load influx in the small dams either and hence the process of blocking up with slime of some of them develops at a surprisingly high pace. This situation reduces their utilization and increases the risk of their overflow in floods, which might result in partial or full demolition of the dams. Danger might emerge any-time if unauthorized actions were undertaken, such as building of superstructure on the dam, or filling in of the spillway, or blocking of the drain cocks with the aim to retain more water in the reservoir. Overflowing of dams might lead to their destruction, which is a potential danger for the nearby human settlements. Conducting of periodical control surveys and measurements for assessment of the technical state-of-repair of the small dams is necessary, however in actual fact this is not done regularly and at the required competence level.

The practice with respect to the operation of small dams reveals a number of omissions and inappropriate activities in the field of maintenance and management, including absence of any hydrometric measurements of the water balance components, the sediment load and sludge building, the quality of water and the sources of pollution, the absence of wastewater treatment facilities at the stock-rearing farms, etc.

Grave environmental problems, affecting the life and health of the human beings, the ecosystems and the environment in general, are created also by the tailing reservoirs, which are in fact water storage facilities of specific designation. Irrespective of their formal compatibility with lakes in terms of morphological properties, they are man-made facilities entirely deprived of life because of the high concentration of pollutants as a result of ore floatation, coal rinsing, technological processes in industry, etc. Averages happening in these facilities, however, have a grave effect on the river environment, the sanitary conditions in the human settlements and all the biocenoses in the host-river. Such a case of negative consequences as a result of the partial destruction of the tailing reservoir at the Maritsa I TPP in the city of Galabovo on the river Sazliyka in 1991 has been studied in detail by the author (Gergov, 1993) – [Photo 1](#), including its development up to the border with Turkey at Svilengrad.

The author has assessed the concentration of pollutants, their distribution, and sedimentation in the riverbed, the speed of their spread along the river network and their gradual dilution. In certain cases, like the one described above, the average might cause also claims from abroad for pollution of trans-border water currents. The above-described case may serve as an example for the negative consequences that might emerge in the event of average of small dams, provided no preventive care is taken.

Some years ago at the decision of a State Commission with the Council of Ministers, a profound technical audit of all such dams was implemented. The results from that audit reveal the following:



Wetland Areas and Lakes in Bulgaria, Photo 1 Destruction of the tail lake at the Galabovo town in 1991.

- Five hundred and twenty-six dams are in a poor technical state-of-repair and in bad need of comprehensive rehabilitation and repair works.
- Ninety-two dams are subject to decommissioning because of their grave damage and hence costly rehabilitation works. This number comprises also 15 potentially dangerous dams.

Another major type of wetland areas spread in the country is undoubtedly that of the river islands. The majority of those situated in the inland rivers are of movable sand-gravel islands, that is, they originate from temporary deposited bottom sediments – [Photo 2](#).

During the periods of low flow some of them become objects of biological stabilization through ample growth of moisture-loving vegetation – grass, bushes, and trees (Raynov et al., 1980). This development converts the temporary piling of river sand and gravel into long-lasting river morphological formation. They undergo periodical changes of their outlines and their height, even full washing away during high water, since they are built of riverbed materials (loose bulk sand and gravel) (Pechinov et al., 1979; Gergov and Nenov, 1984). Economic utilization of some of these islands ([Photo 2](#)) is possible thanks to their long-standing existence. This includes their intensive use as pastures, for timber logging, development of sports and angling facilities, construction of attraction facilities etc. The largest number of islands, however, exists along the Danube River stretches in the Bulgarian section – a total of 147 (Gergov and Nenov, 1984). Some of them are of “river terrace” origin and represent large earth masses of fine deposited material. They have almost unchanging outline as different from movable sediments islands.

River-based sand and gravel quarries – modern modalities of wetland areas

The boom in housing and road construction requires large quantities of sand and gravel. Traditionally, the cheapest method for their provision is their extraction from the riverbeds, where they have been deposited. These raw materials are greatly preferred because of the easy access to them. One major requirement for the setting up of efficient quarry enterprises along the rivers is the availability of large quantities of renewable deposits of sediment load from the river ([Photo 3](#)).

When the productivity of the river bed pits takes into account these deposits, their artificial extraction causes mainly reversible distortions of the riverbed and does not affect gravely the sediment depositions in the river or on its planned and depth-related forms. When, however, the abstraction of sand and gravel from the rivers exceeds the capacity of the river course to recover these, it might cause irreversible distortions of the riverbed at considerable distance above and below the location of the ballast quarry (Kosturkov, 1975; Nenov, 1984) etc.

At many locations the digging of sand and gravel from the riverbeds is performed outside the riverbed on depths, which exceed several times the depth of the river. Some of them occupy dozens of ha of washed away soil and humus cover. The conducted observations reveal that in many cases they are very dangerous deep-water spots for many decades, without any rehabilitation once the operators have left the quarry ([Photo 2](#)). In such cases, mainly ground water fills them and creates standing water mirror, which leads to eutrophication ([Photo 4](#)), followed by gradual filling by vegetation residues and materials from



Wetland Areas and Lakes in Bulgaria, Photo 2 Movable sand-gravel island in the Maritza River near the town of Harmanly.



Wetland Areas and Lakes in Bulgaria, Photo 3 Pilling of the flooded river terrace on the river Malki Iskar at the village of Svode.

crumbling down, the spread of wetland trees and bushes, and creation of a specific micro-climate.

Similar processes develop also in the “tails” of the tailing reservoirs, such as those along the Struma River at the village of Lobosh or at the Koprinka Dam, etc. (Gergov et al., 1983; Gergov and Ninov, 1986).

Five hydrological aspects

Hydrological aspects are assigned an important role in the study of wetland areas. These comprise: typification and

classification, working out the water balance of the affected areas, influx of sediment materials and nutrients; water currents; water pollution.

The practice of operation of the big dams shows that because of the high water losses due to evaporation and feeding the ground water supplies for the purposes of maintaining the water balance, it is necessary to set up hydrometric points at several points along the banks of the water mirror (Gergov, 1974). The hydrological information collected at these points allows accurate



Wetland Areas and Lakes in Bulgaria, Photo 4 Initial eutrophication of a deserted river bed pit in the river Topolnitsa basin.

determination and regulation of the water balance components and, wherever necessary – efficient use and protection of water resources. Such requirements are in force with respect to wetland areas as well, since in their case it is very difficult to identify the feeder province, the exact boundaries of the site and its interaction with natural sites of a similar kind.

The second important direction of hydrological investigations of wetland areas is related to the sediment load transported by the river courses, since they form part of the trophic chains of water species, and their deposition on the bottom contributes to the siltation of the lake and formation of biotope of water ecosystems. It is the depositing of the sediment matter that makes possible the rapid growth of torfaceous vegetation (Gergov, 1996, 2001; Gergov and Karagyozyova, 2002). Some scientists pay special attention to it because of its role as mediator of pollution (Report, Koprinka dam, 1991).

River sediments have, on one hand, mechanical action, which ensues from their depositing on the bottom and lasting accumulation in wetland areas (Gergov, 1989, 2001 and others). The sedimentation of these materials diminishes the water volume in the wetland area and that is a hindrance to the further water exchange in it. A special study on the Lessichevo water reservoir has been conducted (Report Lessichevo, 2000) (Photo 5). The test samples taken from the lake in situ and proper measurements have revealed the following:

- The charging of the water reservoir with sediment matter has developed rapidly and has resulted in complete filling in of its free capacity. This has led to diminishing of its efficiency and opportunities for practical use.

- The grave pollution of the river influx coming from the water catchment with toxic substances and heavy metals from the Medet-Assarel mining has led to accumulation of large quantities of arsenic, copper, etc. on the bottom, which endanger the further use of the water reservoir for irrigation purposes.

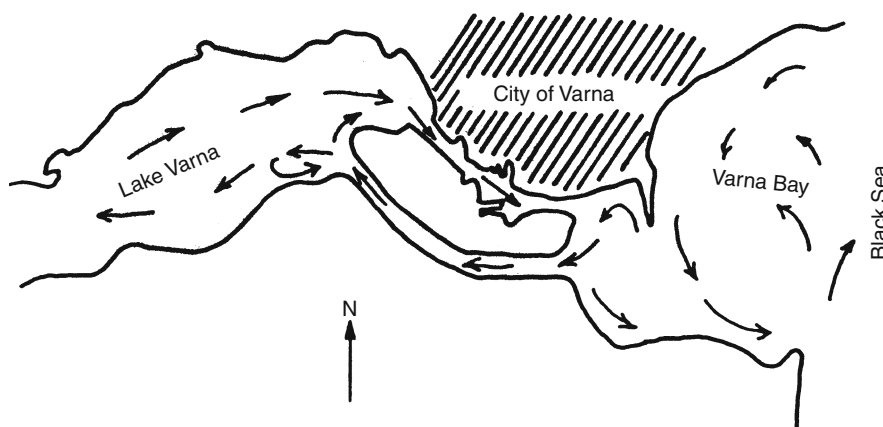
Alternatively, the absence of currents creates favorable conditions for intensive deposition of sediment matter and the development of torfaceous vegetation, which hinders still graver the penetration of fresh water and the emergence of putrefactive processes. In order to prevent such development, it is necessary to set up and maintain water flow there by means of human intervention. This is called forth by the requirement to maintain good conditions for development of the ecosystems and limitation of the eventual development of organisms causing diseases.

In several subsequent investigations of the same bay – detailed on-site measurements and remote sensing measurements, densitometric analysis of photo snaps and analyses of spatial images of the area (Petkova and Gergov, 1983) have corroborated this result. Moreover, it has been found out that at the outlet of the bay there is a current oriented southwards, which runs close to the coastline and can visually be tracked down to the region of the city of Sozopol. These findings are of environmental significance and might serve to help identify the sources of pollution and the mechanism of their distribution across this important holiday making and economic area. Rousenov and Stanev (1986) have worked out also a mathematical model of the currents in the bay.

The very first investigation in Bulgaria of the water currents in a large wetland area – the Beloslavsko Lake and



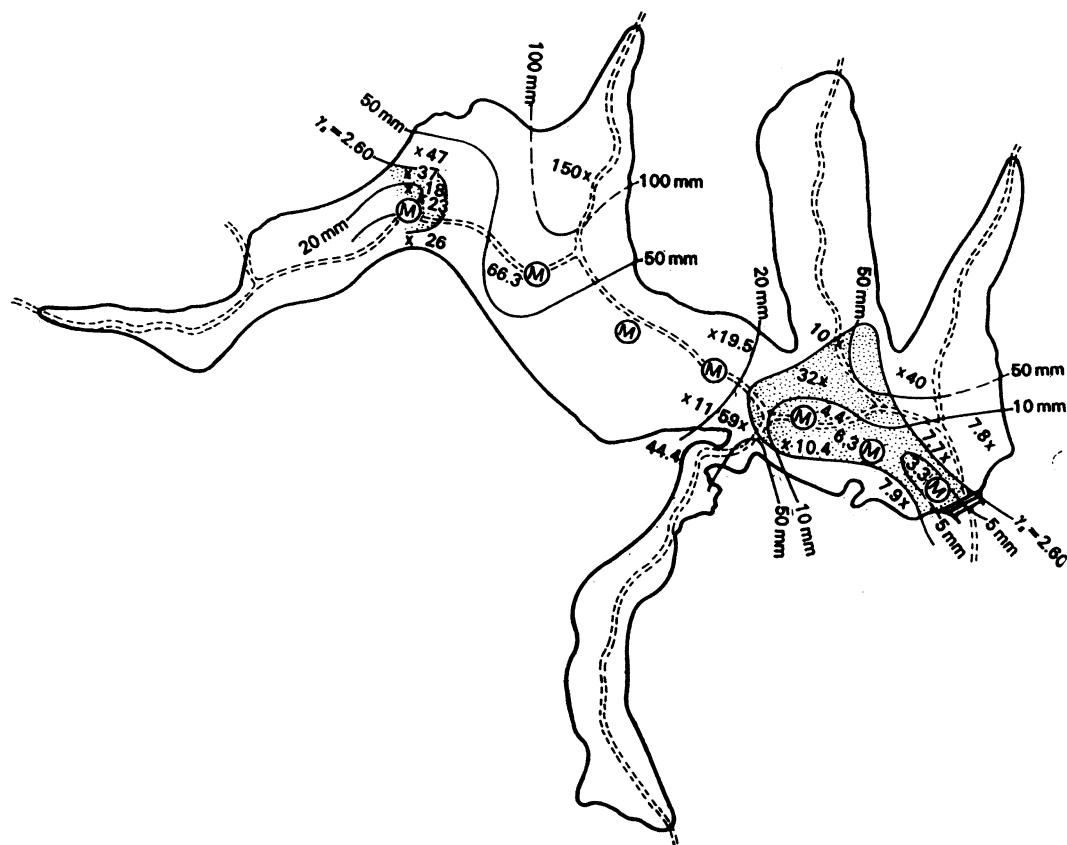
Wetland Areas and Lakes in Bulgaria, Photo 5 The Lessichevo water reservoir is clogged and overgrown with water vegetation.



Wetland Areas and Lakes in Bulgaria, Figure 3 Currents in the Lake-Bay hydro-complex near the city of Varna.

the Varna Bay (Vesselinov and Gergov, 1980; Gergov, 1989) by means of a number of automatic sea propellers type “A.Ott.Kempton” – has revealed the scheme of the currents in this water complex (Figure 3). This has permitted to determine the route of penetration of pollution from the industrial area of the city of Varna, from Devnya and Provadiya, to the city beach on the Varna Bay, to Galata and other beach strips. It has been found that industrially polluted water from the industrial zone of the city of Varna, mixed with stagnant fresh water in the Beloslavsko Lake, enriched with organic contaminants products from the ongoing putrefactive processes there, discharges in the area of the Varna Bay and causes pollution of the

coastal strip and the nearby situated city beach with pollutants of different types and in different concentrations. At the same time, a large portion of the transported sediment load is deposited in the southern end of the bay and forms an underwater sand bank right opposite the entry to the navigation canals, which creates situations of risk for the ships entering the large industrial port from the sea. On the other hand, the salty sea waters rush in the direction of the lakes along the southern canal as a counter current. In this way an intensive intermixture of fresh and seawaters, charged with pollution of different composition and transmitting nutrient environment of different composition. Later investigations have revealed that the above-indicated



Wetland Areas and Lakes in Bulgaria, Figure 4 Distribution of the bottom-level sediments in Koprinka Dam depending on the grain size of sediment particles (Gergov, 1991, 1992).

scheme is dynamic and depends on the meteorological situation and the state of water volume in the lake.

Similar measurements of the currents in Koprinka lake were conducted by means of improved submerging floaters at different water horizons (Report Koprinka, 1991). The results obtained through direct high-depth measurements cast ample light on the underwater local depositions of fine sediment sludge featuring variable granulometric composition in the cup of the dam (Gergov, 1992) (Figure 4).

Anthropogenic impact on wetland areas

The study of the wetland areas involves specific attention to the conducting of engineering activities in the respective region – road building, water abstraction, building of embankments, etc. This is due to the fact that the lessons learned from the past decades have highlighted the fact that the results are negative when a one-sided approach is applied for resolution of the problems, without good knowledge of the possible consequences. One example in this respect is the river Kamchiya mouth in Bulgaria, famous for its vast and beautiful flooded terrace oak forest – Longoza (Raynov et al., 1980). The annual overflows of the river have created full-value wetland area

featuring rich living environment – oak forests, lianas and climbing plants, moor vegetation, a thick layer of rotting dead foliage, and abundance of wild life. The correction of the riverbed in this section has resulted in limitation and even complete abolishment of overflows, which has created a threat to the existence of the rich vegetation diversity. The supply of fresh water, river sediments, and nutrients from the river to the terrace has been cut off. The straight-line shift of the river route has led to increase of the slope of water current and hence of its transport capacity, as a result of which a process of river degradation has begun, involving gradual washing away of the beach strip in the river Kamchiya mouth area and hence reduction of the size of the sediment “torch” opposite it. In this way it has become possible to excavate building components of an ancient port that had existed on that location (Raynov et al. 1974). The negative consequences from the described engineering activities on the state and dimensions of the wetland areas make it urgently necessary to consider the possibility for restoration of the natural equilibrium and full restoration of the famous unique wetland area Longoza through liquidation of all the elements of human intervention in its existence.

Back to nature

In the course of time, the attitude toward wetland areas in the country has changed. Presently, there is a general awareness of their ecological role for maintaining the rich biodiversity. Thanks to the efforts of environmental NGOs, the idea to protect and recover these wetland areas and lakes and revive their role as regulators of natural processes following the example of Great Britain, the USA, Russia, etc., has taken more definite shape.

Conclusions

The above brief presentation of the problems and peculiarities of natural and man-made wetland areas in the country has revealed that they are part of the total national water resources. The political and economic changes that have taken place in the recent years and the latest amendments to the environmental protection legislation of the country require adequate changes in the attitude toward protection of water resources and development of a national strategy for their sustainable and safe use, more specifically the following:

1. All types of wetland areas (natural, man-made, inland, coastal, fresh or salt water ones, etc.) possess unique characteristics, which are not adequately highlighted by the contemporary ecological science.
2. The investigations of the wetland areas require interdisciplinary approach.
3. There is a growing interest in and a drive to the formulation of a stable policy for regulation and management of all types of wetland areas, which calls for the establishment of a sustainable research and information framework, integrated in the form of a strategy for development and conservation of the wetland areas.

The main issues pending resolution with respect to the management of wetland areas comprise prevention of environmental pollution, eutrophication and threat to biodiversity. This gives rise to socioeconomical and legislative issues related to the use and preservation of their resources, the role of the state, local authorities and the individual water end-users in this process etc.

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Cross-references

[Europe, Lakes Review Wetlands](#)

WETLANDS

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Introduction

Wetlands cover a large part of the Earth perhaps of the order of 6% or 1.8 million km² and may be termed habitats between dry land and deep water including marshes,

swamps, peatland, bogs, rivers, streams, ponds, and lakes. Estuaries, coastal waters, salt marshes, mangroves, and coral reefs may also be classified as wetlands. It is estimated that some 75% of the world's population live in former wetlands and surrounding areas. Wetlands are always in a state of change as lakes and ponds dry up or fill with plants or as salt marshes or mangrove swamps gradually extend out to sea.

Wetlands of international importance now include nearly 2,000 sites (known as Ramsar Sites – the Convention on Wetlands). The nation with the most sites is the UK with 168, but the nation with the greatest area of listed wetlands is Canada with over 130,000 km². The world's largest wetland is the Pantanal which straddles Brazil, Bolivia, and Paraguay in South America with Kakadu National Park in Australia not far behind. Scotland contains over 10,500 km² of blanket bog, and the "flow country" there, at some 4,000 km², is probably the largest single expanse of blanket bog in the world.

The Ramsar convention

The Ramsar Convention is an international treaty for the conservation and sustainability of wetlands, their scientific, economical, cultural, and recreational value to the community. The name is from the city of Ramsar in Iran and founded in Ramsar by participating nations there in 1971.

According to the Wildfowl and Wetlands Trust (WWT), half of the world's wetlands have already been lost over the last century, and this is increasing. WWT engages and inspires people, governments, and businesses to take direct action to save wetlands and their wildlife and encourages the creation of wetland centers worldwide.

Reedbeds and fens

In the UK, for example, key reedbeds and fen areas include the Tay estuary, the Norfolk and Suffolk Broads, and Far Ings along the Humber Estuary.

Transboundary Ramsar sites

Transboundary Ramsar Sites (TRS) may extend across national borders, and the Ramsar site authorities on both or all sides of the border have formally agreed to collaborate in its management.

The Ramsar list

The Ramsar List is an official product of the Ramsar Convention on Wetlands and is maintained by the treaty secretariat in collaboration with Wetlands International.

The list is continually updated with every new site added and arranged alphabetically. The list shows the site name, date of designation, region within the country, surface area in hectares, and central geographical coordinates of each site. An annotated Ramsar List is available as a 500-page spiral-bound publication with a paragraph of amplification of each Ramsar site (ramsar@ramsar.org).

Wetlands purification systems

Wetlands may serve as wastewater purification systems where satisfactory dissolved oxygen can be obtained by spreading the wastewater over wetlands. Such examples are in Calcutta and Arcata in California.

Note: The study of wetlands has recently been termed *paludology* in some publications.

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Cross-references

[Everglades, Florida, USA](#)
[Fens, England](#)
[Wetland Areas and Lakes in Bulgaria](#)
[Wetlands: Classification, Distribution, Function](#)

WETLANDS OF THE CANADIAN ARCTIC

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Introduction

The Canadian Arctic is an area north of the treeline. With an area of 2.7 million km², it occupies about one-quarter of the total land area of Canada. Wetlands cover about 3–5% of the Arctic, mostly in the south. Despite their limited extent, they provide an important ecological niche for plants, migratory birds, and animals of the far North. Wetlands can be a sink for atmospheric and terrestrial contaminants; and persistently flooded and high groundwater level in wetlands with carbon-rich soils can give rise to methane production. Arctic wetlands also sequester carbon in the water column, their underlying substrate muds, and through long-term peat accumulation and storage. Drainage leads to the loss of wetlands and disturbance to the peatland can accelerate peat decomposition to release its stored carbon while the removal of peat as an insulator enhances permafrost degradation.

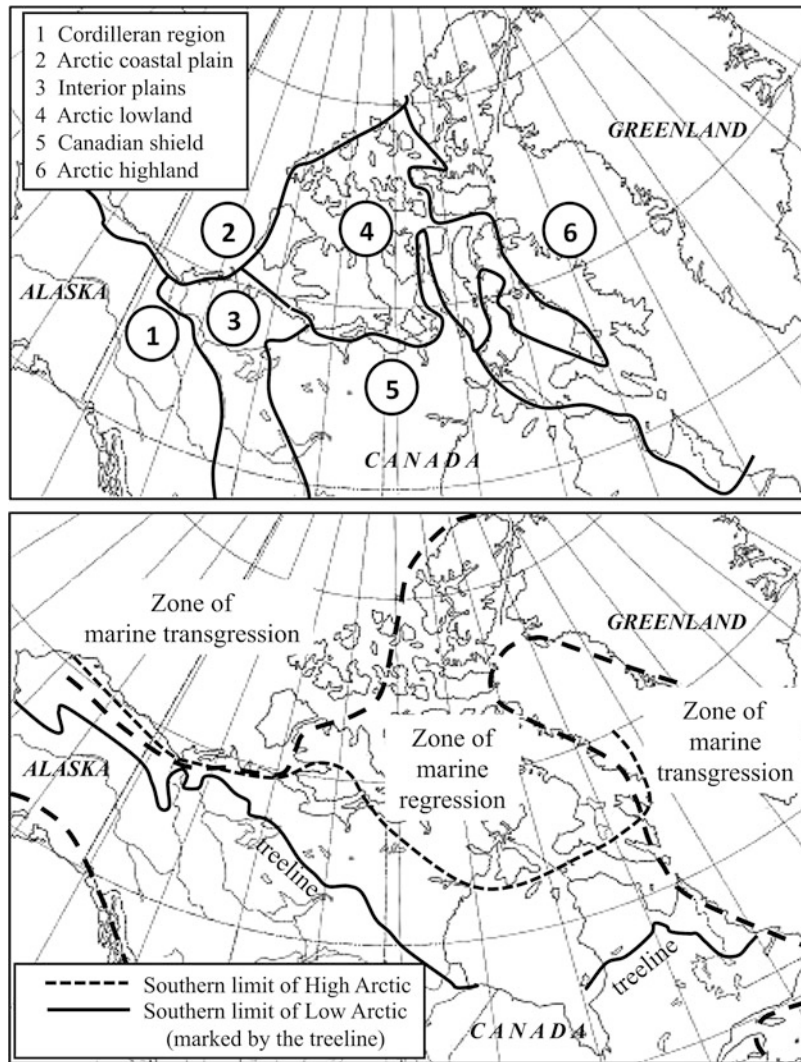
The Canadian Arctic

The Arctic has a harsh climate, with winters that span 9–10 months when mean January air temperature falls below –15°C. In polar regions, solar radiation input is extremely uneven during the year. With up to 24 h of darkness and intense coldness, there is a net radiation loss in several winter months, but in summer, the low level of radiation flux is compensated by long daylight hours. Precipitation is low, usually below 250 mm per year. Only mountainous areas have annual precipitation exceeding 500 mm. Most of the precipitation comes as snow, and with a long cold season, the snow can accumulate to considerable amounts when spring melt arrives. Arctic wetlands benefit from meltwater supply and from frequent fog and low clouds that deposit trace rainfall (0.2 mm per 6-h period) in summer.

Persistent low temperatures are transmitted to the ground to foster the development of permafrost (defined as bedrock, organic or earth material with temperatures at or below 0°C persisting over at least two consecutive summers). Permafrost, when rich in ground ice, tends to be impervious to water flow. Permafrost terrain has a special suite of geomorphic features including patterned grounds, frost cracks and ice-wedge polygons, ice-cored mounds of various dimensions, and thermokarst terrain caused by melting of ground ice in the permafrost followed by land subsidence and surface erosion. All these attributes have an effect on wetland hydrology.

The Canadian Arctic encompasses a range of topography, from coastal plains and deltas to rolling hills of the Canadian Shield and undulating relief of the Arctic Lowland, to rugged mountains of Eastern Arctic ([Figure 1](#)). Topography influences water storage and movement, thus affecting wetland formation. Flat terrain facilitates water stagnation and inundation, rolling topography gives rise to depressions to collect lateral drainage, but steep slopes allow easy drainage. The land surface of the Arctic is largely barren in the High Arctic, and wetlands offer isolated patches with more vegetation than their surrounding polar desert.

Vegetation increases in density and diversity from the High to the Low Arctic. Mats of algae (normally blue-green spp.) are common in both saline and freshwater pond substrates. Wetland vegetation comprises largely mosses and herbaceous plants. *Sphagnum* moss occurs prevalently, as do sedges (*Carex* spp.), cotton grass (*Eriophorum* spp.), and graminoids. Drier tops of sedge hummocks and pond rims typically give rise to Arctic Willow (*Salix arctica*), Arctic Avens (*Dryas integrifolia*), Arctic Poppy (*Papaver radicum*), and a variety of *Saxifraga* spp., *Draba* spp., and Lousewort (*Pedicularis* spp.). Lichen ground cover is minimal in High Arctic wetlands (Woo and Young, 2003) but can be found frequently in the Low Arctic where they usually coexist with moss and peat. Toward the southern fringes of the Low Arctic, shrubs (*Betula* spp. and taller *Salix* spp.) and Ericaceous shrubs such as Labrador Tea (*Ledum palustre*) and Blueberry (*Vaccinium uliginosum*) become increasingly luxurious.



Wetlands of the Canadian Arctic, Figure 1 (top) Physiographic regions of Canadian Arctic. (bottom) Southern limit of the Arctic and zones of marine transgression and regression.

Occurrence of wetlands

A wetland is defined as “lands saturated for most parts of the growing season to allow the development of hydric soils, or support of hydrophytes or prolonged flooding up to a depth of 2 m” (National Wetlands Working Group, 1988). The occurrence of wetlands is affected by three major factors:

1. *Climate*: An excess of precipitation over evaporation will ensure ample water supply to a wetland. Despite low precipitation of the Arctic, evaporation rate is restricted by low supply of energy so that wetlands are found in this semi-arid environment where inputs from lateral sources provide adequate water to maintain wetlands.
2. *Topography*: Depressions and low-lying areas collect and store water, while areas of low gradient have

sluggish flow and retain water for protracted periods to sustain wetlands. Wetlands are found on steep terrain only where local water supply is ample, such as below melting snowbanks and in front of glaciers.

3. *Soil*: Most Arctic wetlands are underlain by peat which has high capacity to retain moisture. Within or below the peat layer is perennially frozen soil which prevents vertical water loss to percolation, allowing the water table to stay close to the surface.

Wetlands are a hydrological feature, and as such, a hydrology-related classification scheme is most appropriate. The Canadian wetland classification system recognizes several types of wetlands: bogs, fens, marshes, swamps, and shallow open waters. Hydrological interpretation can be attached to each wetland type.

1. Bogs obtain moisture mainly from the atmosphere (rain, snow, fog) and shed water to its surroundings. They are thus poor in nutrients.
2. Fens receive lateral drainage from surface and subsurface sources in addition to atmospheric water. They generally have a high water table and are supplied with nutrients from their adjacent lands.
3. Marshes and swamps occur in areas subject to lateral inundation for various durations by rivers, lakes, or the sea. They have standing water or gentle flow conditions. Swamps are distinguished from marshes by the growth of trees and luxuriant shrubs. Since Arctic wetlands lie above the treeline, swamps are not part of the consideration.
4. Ponds are shallow water bodies arbitrarily distinguished from lakes on the basis of water depth. Their depth in the summer never reaches 2 m, and the pond water usually freezes to the bottom in winter.

An Arctic wetland can belong to one of the above categories, or it is a combination of two or more of the wetland types. Thus, the lower part of a fen may merge with a marsh that is inundated by a lake, or a bog can coexist with a fen in different parts of a wetland.

Arctic wetlands

Arctic wetlands occur as isolated patches with areas of 1–10 km², or they cover extensive areas from the meso-scale (10–100 km²) to the regional scale (>100 km²). Patchy wetlands are particularly common in the High Arctic. Extensive wetlands are commonly encountered on low-lying plains.

Patchy wetlands

Based on hydrogeomorphology, Woo and Young (2003) recognized several types of patchy wetlands based mainly on their position in the landscape and their water source which includes snowmelt, groundwater, surface runoff, and inundation by freshwater (rivers and lakes) or the sea. Figure 2 is a conceptualization of occurrence of patchy wetlands in the Arctic.

Wetlands below snowbanks

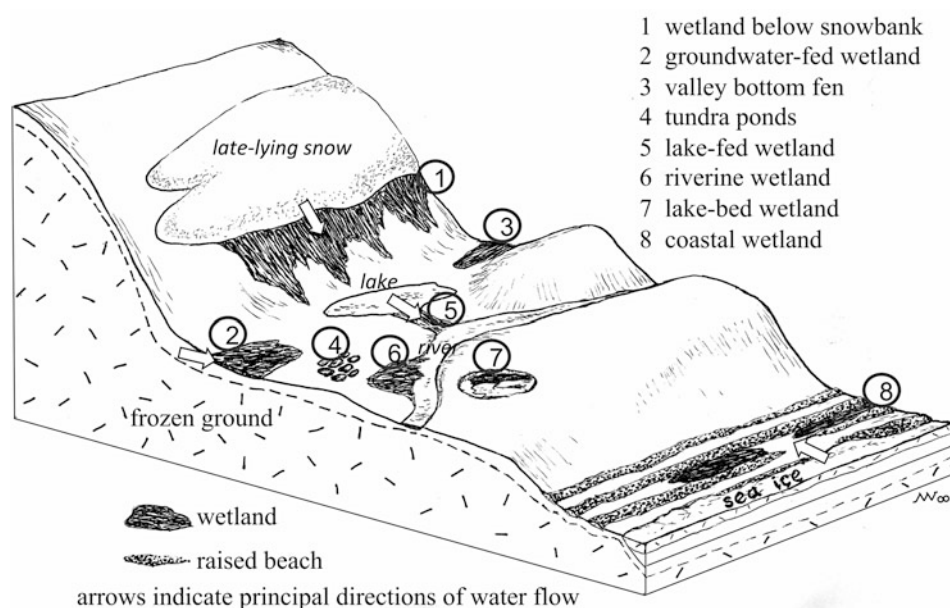
Deep snowbanks are built up on hillslopes by long periods of snow drifting in the winter. A snowbank can become semi-permanent if not completely ablated in one summer. Melting of a late-lying or perennial snowbank yields a steady supply of water to the patchy wetland downslope. The extent of the wetland changes during the summer, expanding upslope as the snowbank shrinks. Vegetation is poorly developed on the upslope side of the wetland as it usually has a limited time of emergence from under the snow cover.

Groundwater-fed wetlands

Where groundwater discharges at the land surface, usually in a depression or at a slope concavity, a high water table is maintained locally in support of a patchy wetland. Although winter snow accumulation on the wetland is a good water source, groundwater in the active layer (the seasonally thawed layer on top of the permafrost) provides reliable water supply to sustain the wetland.

Valley bottom fens

A fen may occupy a flat-bottomed valley when wetness is maintained by surface and sub surface drainage from the



Wetlands of the Canadian Arctic, Figure 2 Conceptualization of occurrence of patchy wetlands in the Arctic.

adjacent slopes. It is a variant of groundwater-fed wetland without dependable water supply during the dry season, when the fen is hydrologically uncoupled from the hillslopes.

Wetlands due to lateral inundation

Lateral flooding of land on the banks of rivers, along the shores of lakes and at the coastal margins, gives rise to strips of patchy wetland. Riverine and lakeshore marshes are subject to large floods in the snowmelt period and become increasingly exposed as river and lake levels drop seasonally. Coastal marshes are saline in nature, and their extent and level of flooding are influenced by the tide. With isostatic rebound after deglaciation occurring in most of Canadian Arctic (areas subject to marine regression, shown in Figure 1), coastal marshes are gradually lifted above the high water mark, and over decades and centuries, the old marshes become dry land, while new marshes are created on the seaward side. Marine transgression (sea level rises relative to elevation of the land) also occurs in some other Arctic areas (Figure 1). There, new wetlands are created, altered, or drained in response to coastal submergence, tidal activity, and interactions with sea ice which can erode and modify the coastline.

Tundra ponds

Unique to the Arctic are tundra ponds that are formed inside low-centered polygons (patterned ground with raised rims of large cracks measuring 10^1 – 10^2 m in length enclosing polygonal-shaped central zone) or that occupy the enlarged cracks of ice-wedge polygons. Tundra ponds are usually found singly or in a cluster, the latter may or may not be connected by surface and subsurface flows (Woo and Guan, 2006).

Lake-fed and lake-bed wetlands

Outflow and seepage from lakes and large ponds may be sufficiently continuous during the thaw season to maintain patchy wetlands below the outlets. Water supply to the lake-fed wetlands depends on the lake level which generally declines after the snowmelt season. Lakes may have drained or dry out after a long period of low precipitation and high evaporation. Ponds and patchy wetlands may then be found on the former lake beds.

Extensive wetlands

Extensive wetlands situated in the Canadian Low Arctic and High Arctic can best be described as a mosaic of patchy wetland types: ponds, lakes, wet meadows, saturated ground, inter-mixed with patches of dry ground. There are wetlands where one or more components (e.g., ponds, wet meadows) can dominate the landscape (Woo and Young, 2006).

Wet terrain

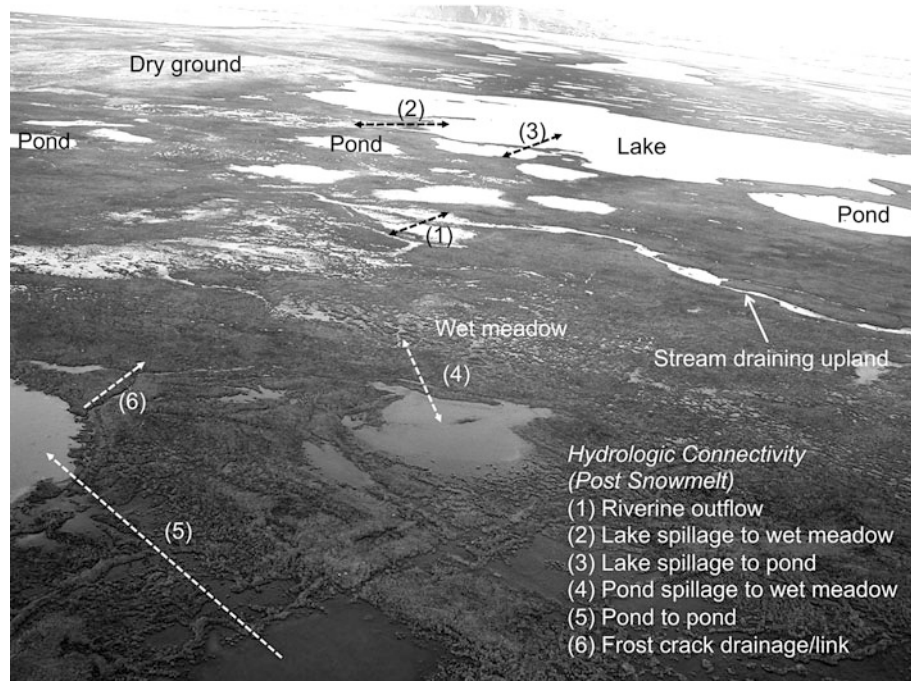
Seasonal snowmelt is an important source of water for ponds, wet meadow, and wet ground. It recharges wetland

storage, enables strong hydrological linkages, and transfers sediment, terrestrial carbon, and nutrients. In the post-snowmelt season with warm, dry periods, evaporation losses and vertical seepage draw down the water table, lower the soil moisture content, and reduce the wetland storage. Hydrologic connectivity is generally severed between most ponds and wet meadows though linkages may endure locally where the wetland continues to be fed by late-lying snowbeds, creeks, and ground ice melt. Ponds and wet meadow zones dry out periodically due to rapid drainage which may be associated with thawing of their underlying coarse substrates or is caused by the presence of linear frost cracks lying at lower elevations that lead the water away from the wetlands (Abnizova and Young, 2010) (Figure 3). Timing and duration of summer rains are critical. Directly following snowmelt, they help to prolong high water levels and connectivity, but rainfall late in the season may not match evaporation losses and vertical seepage. However, if frequent enough, multiple small rain events may prime the wetlands for a high rainfall event (e.g., >20 mm) to rejuvenate floods and widespread runoff that match the spring freshets.

Ice-wedge polygon fields

Ice-wedge polygon fields are found in many parts of Arctic Canada. Polar Bear Pass, centrally located on Bathurst Island, provides an example of a network of low-centered polygons. It is an ecologically important area in the Arctic Archipelago and has been designated a wildlife sanctuary, offering a favorable habitat for migratory birds, caribou, muskox, and polar bears. Local Inuit frequently travel there to hunt for caribou. Many small tundra ponds occupy the shallow depressions surrounded by raised vegetated rims of the ice-wedge polygons. The ponds occasionally join with their adjacent sedge-dominated wet meadows to produce larger ponds or lakes (Figure 4). As of summer 2010, this low-gradient regional wetland (100 km²) included 4,800 regular (rectangular) and irregular-shaped ponds and two large lakes.

After a cold, long winter that lasts for about 9 months, snowmelt begins in early June. In 2–4 weeks, most of the snow on the wetland is depleted, ponds and wet meadows are recharged, and hydrologic linkages are established among all wetland types (ponds, wet meadows, and wet grounds). For ponds and meadows lying along the edges of Polar Bear Pass and adjacent to steep slopes and elevated plateaus, the influx of water and nutrients is prolonged for several weeks due to contributions from late-lying snowbeds on the lee of slopes and from the many ephemeral creeks draining from the uplands. This supplemental water supply buffers these wetland zones from water losses to high evaporation and to vertical seepage as the ground thaws in the summer. In the interior of the polygon wetland field, high ice content retards ground thaw to keep the water table elevated while some water is added to the wetland as the ground ice melts. There are minimal groundwater exchanges among the interior ponds, but evaporation causes a steady decline of the pond levels. Like other



Wetlands of the Canadian Arctic, Figure 3 Wet terrain in northern Somerset Island, showing different terrain types and their hydrologic linkages.



Wetlands of the Canadian Arctic, Figure 4 Ice-wedge polygon field in Polar Bear Pass, Bathurst Island, with *rectangular* and *irregularly shaped polygons*.

extensive wetlands, the status and the capacity of wetland storage (in the ponds and wet meadows) influence the wetland response to rainfall. Small and frequent summer rainfall events can raise the antecedent moisture storage

status. Freshet conditions (high pond levels, saturated wet meadows, and extensive runoff) can be raised by large rainfall events only if local storage capacities are exceeded (Young et al., 2010).

Deltas

Arctic deltas are often a combination of river channels, relatively high grounds such as levees, wetlands, and lakes (shallow ones are also considered as standing water wetlands). Deltaic wetlands are flooded by high flows associated with annual river breakups. The magnitude of floods is amplified by river ice jams that block the flow until the jams burst. However, spring freshet does not necessarily lead to complete inundation of all wetlands in a large delta. For example, shallow lakes of the Mackenzie River delta are grouped into categories of “no-closure lakes” that are flooded throughout the summer, “low-closure lakes” that are flooded each spring but infrequently flooded in the summer, and “high-closure lakes” that receive spring floods only during years with large freshets and are never flooded in the summer (Marsh and Hey, 1989).

Storm surges are due to wind stress on the water surface to produce a large displacement of water. Owing to low relief, episodic storm surges can produce backwater effects that raise the river stage to drown deltaic wetlands, as happened in the Mackenzie Delta on September 15–18, 1985 (Marsh and Schmidt, 1993). It produced backwater effect up the river to as far as over 200 km inland. The high water level led to flooding of many deltaic lakes and wetlands and affected the sediment, chemical, nutrient, and energy inputs to the deltaic area.

Flat lands

Most Arctic flat lands are associated with coastal plains. The high grounds are covered by tundra and dissected by ice-wedge polygons. Many lakes are present, including those that are partially or have completely drained. The tundra drops by low scarps of about 1–2 m to the floors of drained thaw lake basins, often occupied by marshy wetlands and water bodies. For areas undergoing isostatic rebound, the coastal plain has flights of subparallel raised beaches enclosing ponds, marshes, and fens.

With low relief but with little obstruction to snow drifting, winter snow is subject to redistribution to infill depressions and valleys. Spring is the major period of meltwater release. Substantial snowmelt runoff from upslope is the main water supply that replenishes wetland storage. Wetland areas expand to their maximum extent, while high flows are generated in the rivers crossing or issued from the wetlands. With good flow connectivity, runoff can reach the wetland quickly but can also be conveyed out of the wetlands efficiently. After snowmelt, the flooded areas contract quickly, terminating many of the temporary flow linkages within days. The isolated wet patches shrink in size during the summer as water is lost to evapotranspiration. Rain events may raise the water level but are much less effective in enlarging the wet areas than snowmelt. The above hydrologic behavior has been described by Bowling et al. (2003) for the wetlands of the Alaskan Arctic Coastal Plain which is contiguous with the coastal plains of Yukon and Northwest Territories.

Flow paths in wetlands

The flow within and out of wetlands follows surface and subsurface pathways. Wetlands undergo general inundation when ample water from vertical inputs (snow and ice melt, rainfall) and from lateral sources (lake and river floods, tidal rise, upland runoff) raises the water level on the wetland. The modes of surface runoff include (1) overland flow following ill-defined paths around low mounds or narrow strips of drier land on wetland surfaces, (2) spillage from puddles, ponds, and lakes as they become full, and (3) channeled flow in rills, gullies, and streams that cut through the wetland. Overland outflow and spillage take place when storage is filled to capacity and water spills over vegetated borders and pond rims. Channeled flow follows rills between tussocks and hummocks, cracks along and across the rims of ice-wedge polygons, and gullies enlarged through ground ice melt (Abnizova and Young, 2008). There may also be well-marked streams flowing across the wetland, with varying degree of hydrological exchanges between the river and the wetland depending on their relative water levels. These different modes of flow often alternate or merge with each other within a wetland.

Subsurface drainage of wetlands includes vertical seepage and lateral flow. Vertical drainage is limited by the presence of seasonal frost and permafrost not far below the surface, and is much affected by the hydraulic property of peat and mineral soil. As frozen soil rich in ground ice tends to be impervious, subsurface flow is largely confined to the thawed zone. Much water can seep into coarse soils and flow out of the wetland where the hydraulic gradient is steep (Abnizova and Young, 2010). Upon thawing, the peat and its living plant cover may be distinguished generally into a top layer that allows water to move more freely (called the acrotelm) than the more humified, compacted, and less porous peat of the bottom layer (known as the catotelm). When the water table resides in the acrotelm, much of the flow moves through its soil matrix as well as in the soil pipes formed in the peat. A combination of pipeflow and subsurface flow in the acrotelm constitutes quick flow, as distinguished from the slow flow in the catotelm and in the mineral soil below. Such a two-layer flow system (Carey and Woo, 2001) is common in organic soil terrain.

The delivery of water within and from an Arctic wetland depends on the connectivity of flow pathways. Spring freshet is the prime time for storage recharge, and once accomplished, surplus waters can be shed from the wetland. Although the overall snow cover pattern is similar between years, slight changes in snow distribution alter the runoff pathways and linkages within a wetland (pond to pond, pond to wet meadow, etc.). The prevalence of frozen grounds in all wetlands during snowmelt encourages flooding and overland flow, offering strong connectivity within the wetland and with nonwetland zones in the catchment, thereby allowing easy transfer of water and nutrients. After the melt season, water level drops, the

flooded and saturated areas contract, and flow linkages among the depressions and between flow conduits are weakened or broken. Nevertheless, connectivity may resume in the summer if heavy rainfall can raise the water levels above the storage capacity of the wet terrain. Such seasonal enlargement and contraction of wet areas are commonly observed in Arctic wetlands of Canada and Alaska. The fill-and-spill mechanism, applied to chains of lakes (Woo and Mielko, 2007), appropriately describes the expansion and contraction of surface ponding and flow connectivity. Ponds expand as they are filled. Spillage of individual ponds occurs when their levels reach the elevations of their outlet lips. Overflow provides runoff that establishes linkages among ponds and integrates the wetland drainage network.

The fill-and-spill principle also applies to subsurface flow as the ground thaws. Differential thaw rates within a wetland give rise to an uneven frost table with many troughs and depressions that temporarily withhold supra-permafrost groundwater from lateral drainage. When sufficient water is accumulated, subsurface flow occurs as water spills over the subterranean sill.

Hydrology of wetlands

Water balance

To survive over time, a wetland needs a positive water storage during most of the thawed season to maintain a high degree of saturation, necessitating the total water input to exceed cumulative water loss:

$$dS/dt = [P + Q_{in}] - [E + Q_{out}]. \quad (1)$$

Here, dS/dt is change in storage during time interval dt , $P = S_n + R$ is precipitation and includes both snowfall (S_n) and rainfall (R). Q_{in} is inputs into the wetland system from surface and subsurface sources. Losses of water from wetlands include evaporation (E) from open water and adjacent wet areas which tend to expand and shrink over a summer season, and water losses to groundwater and surface runoff from the wetland (Q_{out}). Table 1 presents values of water balance components for selected wetlands across the Arctic. At each site, only one to several years of study was carried out, and the water balance period usually spans over most of the thaw season, from snowmelt until late summer.

Wetlands derive their water from direct precipitation that includes rainfall and snowfall, the latter may be stored over winter and subsequently released as snowmelt, melting of ground ice which may have been held in storage seasonally or over longer periods, lateral inputs that can be spillage from lakes and rivers, coastal inundation, surface and groundwater inflows from nearby hillslopes, or from upstream catchments. There is much variability in rainfall across the Arctic. Table 2 summarizes the annual rainfall along a north-south transect of weather stations in central and western Canada where vast tracts of Arctic wetland are located. Rainfall decreases northward, from over 200 mm in the Low Arctic to 50 mm or less in

the High Arctic. On a mesoscale, wetlands in polar oases (many of which are in rain shadow areas) receive less rain than polar desert sites; greater exposure to open water and frequent passage of low pressure systems generally deposits more rainfall and high elevations have more precipitation (Young et al., 2006).

Snow is particularly important, and for Arctic wetlands, it is the total winter snow accumulation rather than snowfall of individual events that is of major hydrological consequence. Melting of snow replenishes storage deficits at the beginning of a new hydrological year so that wetlands start off with saturated conditions for plant growth and provides adequate storage to buffer against summer drought and evaporation losses. Despite months of accumulation, total snow accumulation is around 100 mm (snow water equivalent) in a given winter, reflecting the dry and cold environment. There are regional variations. For instance, snowpacks of <100 mm are the norm for polar oasis-type climate, while wetlands in the polar desert capture 100–200 mm and occasionally >200 mm in ponds situated in deep depressions (Abnizova and Young, 2010).

Between the termination of the main snowmelt season and the end of summer, much of the water in wetlands is lost to evaporation. Table 3 indicates that daily mean evaporation is usually lower in the High Arctic than in the Low Arctic, which has a longer thaw season without a snow and ice cover. However, during warm, dry summers in the High Arctic, daily rates and seasonal totals can approach levels typical of Low Arctic sites, even under polar desert climatic conditions (Young and Labine, 2010). Evaporation is lower at coastal wetlands (e.g., Prudhoe Bay in Alaska) owing to low air temperature, and foggy, damp conditions which reduce energy receipt. Further inland, advection from heated ground adjacent to the wetland accelerates evaporation (e.g., open water bodies in the Mackenzie Delta). In terms of wetland terrain units, ponds generally have higher rates of evaporation than wet meadow zones.

Limited records on seasonal outflow from wetlands are available to assess the ratio of runoff to precipitation, known as the runoff ratio or Q_{out}/P . Table 1 provides examples from wetlands in the Low Arctic and the High Arctic. The ratio seldom exceeds 0.50, suggesting that wetlands are effective in withholding water through surface storage (topographic depressions including ponds; water later lost to infiltration or evaporation), or releasing it directly to evaporation and lateral flow. At the end of the study years, wetland storage is often negative as the stored water is reduced by evaporation. Negative storage may also be an artifact of the duration of the study periods which often terminated around mid-August before the onset of late summer rainfall that can recharge wetland storage.

Seasonality

Other than coastal wetlands which are dominated by tidal rhythms, the delivery of water within and from an Arctic wetland is strongly seasonal. A freshet is common in the

Wetlands of the Canadian Arctic, Table 1 Components of water balance for selected extensive wetlands in Low Arctic and High Arctic Canada (all values in mm). Values from Alaska are provided for comparison

Basin	Description & area	Year	Sn	R	P = Sn + R	Q _{out}	E	dS/dt	Q _{out} /P
Low Arctic Coastal plain, Prudhoe bay, Alaska (70°26'N, 148°53'W) Rovensek et al. (1996)	Tundra ponds (located in a 0.224 km ² study area)	1992	NA	NA	50	NA	165	-156	NA
		1993	NA	NA	71	NA	201	-162	NA
Low Arctic Putuligayuk, Watershed, Coastal plain, Alaska (70°N, 148°45'W) Bowling et al. (2003)	Tundra sedge/shrub (471 km ²)	1999	81	172	253	49	188	-2	0.19
		2000	117	146	263	87	161	-25	0.33
		2001	93	NA	NA	56	NA	NA	NA
High Arctic Intensive Watershed, Coastal Wetland, Devon Island (76°N 85°W) Rydén (1977)	63% vegetated and bare soil, 12% water, 25% bedrock (0.12 km ²)	1972	132	36	168	66	69(32) ^a	1	0.39
		1973	111	73	184	83	110(41)	-50	0.45
		1974	169	35	204	101	65(34)	4	0.50
High Arctic Eastwind Lake (80°08'N, 85°35'W) Woo and Guan (2006) (cluster of tundra ponds)	P1 (1080 m ²)	2005	NA	27	NA	NA	155	-53[-75] ^b	NA
	P2 (2056 m ²)	12 June – 11 August (post snow-melt)	NA	27	NA	NA	163	-67[-69]	NA
	P3 (1494 m ²)		NA	27	NA	NA	157	-110[-20]	NA
	P4 (1211 m ²)		NA	27	NA	NA	159	-110[-22]	NA
	P5 (2104 m ²)		NA	27	NA	NA	156	-54[-75]	NA
	P6 (3376 m ²)		NA	27	NA	NA	156	-33[-96]	NA
<i>(includes open water and wet meadow inside the ponds)</i>									
High Arctic Creswell bay (72°43'N, 94°15'W) Abnizova and Young (2010) (medium-sized ponds)	Moraine (149 m ²)	2005 19 June – 12 August	NA	45	NA	NA	103	-140[-82] ^b	NA
	Plateau (1074 m ²)		NA	45	NA	NA	117	-125[-50]	NA
	Coastal (1386 m ²)	(post snow-melt)	NA	45	NA	NA	120	-130[-54]	NA
	Bedrock (646 m ²)		NA	45	NA	NA	132	-130[-43]	NA
	Moraine (149 m ²)	2006 19 June – 25 July (post snow-melt)	NA	42	NA	NA	84	-15 [27] ^b	NA
	Plateau (1074 m ²)		NA	42	NA	NA	92	-203[-153]	NA
	Coastal (1386 m ²)		NA	42	NA	NA	92	-220[-170]	NA
	Bedrock (646 m ²)		NA	42	NA	NA	96	-149[-96]	NA

P precipitation, Sn snowfall, R rainfall, Q_{out} runoff, E evaporation, dS/dt change in storage

^aindicates sublimation (Rydén, 1977)

^bChange in storage (dS/dt) for Eastwind Lake (Woo and Guan, 2006) and Creswell Bay (Abnizova and Young, 2010): first number is measured and the second number in square brackets is the residual obtained from [(P-E)-dS/dt]

Wetlands of the Canadian Arctic, Table 2 Mean annual rainfall and precipitation (in mm, for 1971–2000) at selected stations in Arctic Canada (Source: Environment Canada)

Station	Latitude and longitude	Rainfall	Precipitation
Alert	81°31'N, 62°16'W	16	154
Mould bay	76°14'N, 119°20'W	27	111
Sachs harbour	72°00'N, 125°16'W	52	149
Cape parry	70°10'N, 124°43'W	67	157
Tuktoyatuk	69°27'N, 133°00'W	75	168
Cambridge bay	69°06'N, 105°08'W	70	139
Inuvik	68°18'N, 133°28'W	117	248
Baker lake	64°17'N, 96°04'W	157	270
Rankin inlet	62°49'N, 92°07'W	182	297

spring due to rapid melting of snow accumulated over the long Arctic winter. The amount, timing, and duration of snowmelt vary according to topography and its interaction with local wind in the High Arctic, with tall vegetation being an additional factor in the Low Arctic. Snowmelt season arrives later and is more protracted in the High Arctic

than the Low Arctic. Within the High Arctic, melt generally occurs earlier and ends sooner at wetlands in a polar oasis (e.g., Eastwind Lake, 80°08'N, 85°35'W) than in the polar desert (e.g., Creswell Bay, 72°42'N, 94°15'W). There are also large interannual variations. Figure 5 illustrates that, even for the same wetland, the timing and the duration of melt differ from year to year according to weather conditions. Cloudy, cool springs can prolong the melt season by a few weeks. Owing to the diverse terrain (ponds, lakes, wet meadows, dry and saturated ground) that constitutes the extensive wetlands, snow cover and melt patterns are also spatially and temporally variable, with deeper snowpacks persisting longer than thin snow patches (Figure 6). Melting of ice in the ponds and on wetland surfaces begins after the snow is ablated. Residual snow and ice often remains on the wetland at the time of spring flooding.

Wetland streams emerge from their winter dormancy of no flow or low flow when the snowmelt season arrives. The initiation of streamflow in wetland catchments lags behind snowmelt by 1–2 weeks, with a more extended delay for large rivers and in cold and cloudy springs. The delay is attributed to the time needed for the meltwater

Wetlands of the Canadian Arctic, Table 3 Rates of daily evaporation (mm d^{-1}) from selected Arctic wetlands

Location	Wetland type	Period	Evaporation	Reference
<i>Low Arctic</i>				
Prudhoe bay, Alaska	Pond	9 June–14 Sept 1992	2.0 ^a	Rovansek et al. (1996)
		29 May–11 Sept 1993	2.1 ^a	
Putuligayuk river, Alaska	Pond	10 June–15 Sept 1999	1.9 ^a	Bowling et al. (2003)
		17 June–13 Sept 2000	1.8 ^a	
Baker lake, NWT	Sedge-moss fen	22 June–1 Aug 1983	2.2–7.3 (4.5 ^a)	Roulet and Woo (1986)
Mackenzie river delta, NWT	Pond (NRC lake)	7 June–31 Aug 1984	2.9 ^a	Marsh and Bigras (1988)
		9 June –1 Sept 1985	2.8 ^a	
		16 June–2 Sept 1986	2.5 ^a	
	Pond (Dishwater lake subject to heat advection)	15 June–11 Sept 1982	3.9 ^a	
		15 June–1 Sept 1983	4.1 ^a	
		7 June–29 Aug 1984	4.6 ^a	
		9 Jun–27 Aug 1985	3.9 ^a	
<i>High Arctic</i>				
Hot weather Ck., Ellesmere Island	Sedge-moss fen	7 June–8 Aug 1993	0.5–3.8	Glenn and Woo (1997)
Eastwind lake, Ellesmere Island	Pond	12 June – 11 Aug 2005	0.9–4.7	Woo and Guan (2006)
	Wet meadow		1.0–4.3	
Resolute, Cornwallis Island	Patchy wetland	29 June–8 Aug 1997 (cool and wet)	1.6 ^a	Young and Woo (2003)
		14 June–8 Aug 1998 (warm and dry)	2.6 ^a	
Creswell bay, Somerset Island	Sedge-moss fen	July 2005	1.3 ^a	Abnizova and Young (2010)
	Pond		1.8 ^a	
	Sedge-moss fen	July 1 –July 25 2006	1.6 ^a	
	Pond		2.2 ^a	Young and Labine (2010)
Polar bear pass, Bathurst Island	Sedge-moss fen	July 2007 (warm and dry)	0.4–4.0 (3.0 ^a)	
	Pond		0.5–5.9 (4.2 ^a)	
	Sedge-moss fen	July 2008 (wet: 96 mm rain)	0.2–3.1 (1.6 ^a)	
	Pond		0.8–4.8 (2.6 ^a)	

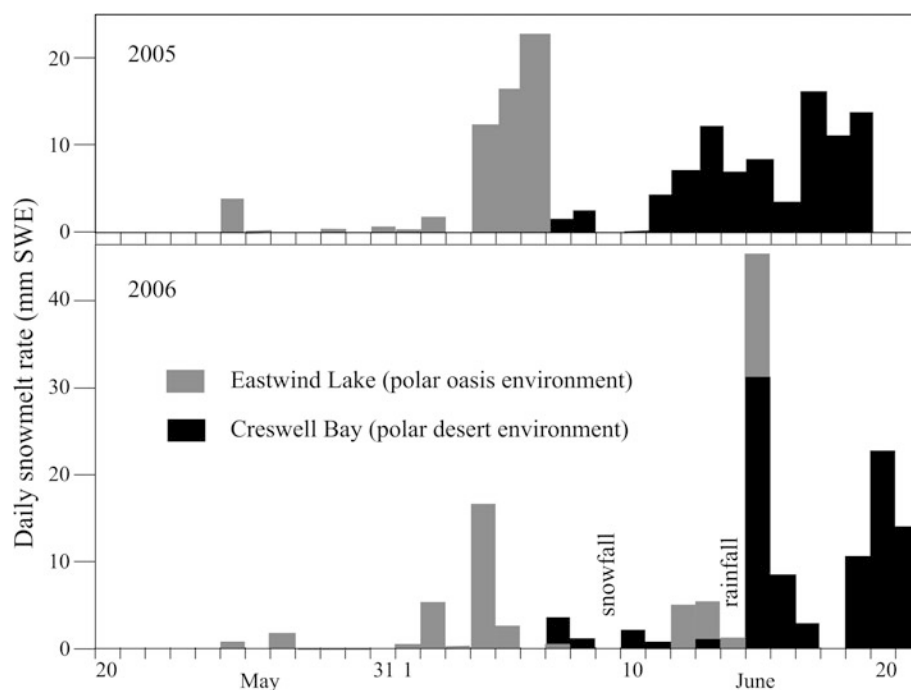
^aindicates daily mean, otherwise the numbers indicate the range of daily evaporation during the study period

(1) to percolate the snowpack to reach the ground, including the refreezing meltwater to form ice lenses in the cold snow, or the possibility of infiltration into porous soils; (2) to satisfy wetland storage requirements, such as filling surface depressions and ponds; (3) to travel across the wetland as overland flow and through the thawed portion of the acrotelm; and (4) to clear the channels within the wetland which are usually infilled with snow and ice that block the flow. Spring peak discharges are attained when the wetland drainage network is connected for flow delivery, and peaks are magnified by snow and ice breakup events in the channels. For some large wetland rivers, peak discharge may not occur until over a week after the end of the main snowmelt season (Figure 7).

Subsequently, discharge recedes as evaporation intensifies and storage declines. Evaporation becomes active when wetlands are shed of their snow and ice cover, and the intensity of evaporation depends on the availability of water and energy, the surface to air vapor pressure gradient, and the intensity of turbulent motion. Surface cover (percentage open water and bare or vegetated land) and vegetation type (woody, vascular or nonvascular plants) further modify evaporation rates. When snow disappears from a wetland, the freshly exposed surface has a high moisture content. Ample available moisture and large

input of energy in June to early July enable high evaporation in the immediate post-melt period, as evidenced in the daily evaporation rates of a site near Creswell Bay in the High Arctic (Figure 7). Evaporation declines when the wetland becomes drier and solar radiation becomes lower in late summer. Superimposed on this seasonal trend are daily variations due to the weather: evaporation is much reduced on rainy days with low radiation input. Plant growth adds transpiration loss, but lichens and mosses, being nontranspiring, can hinder evaporation by cladding a dry cover over the wet substrate.

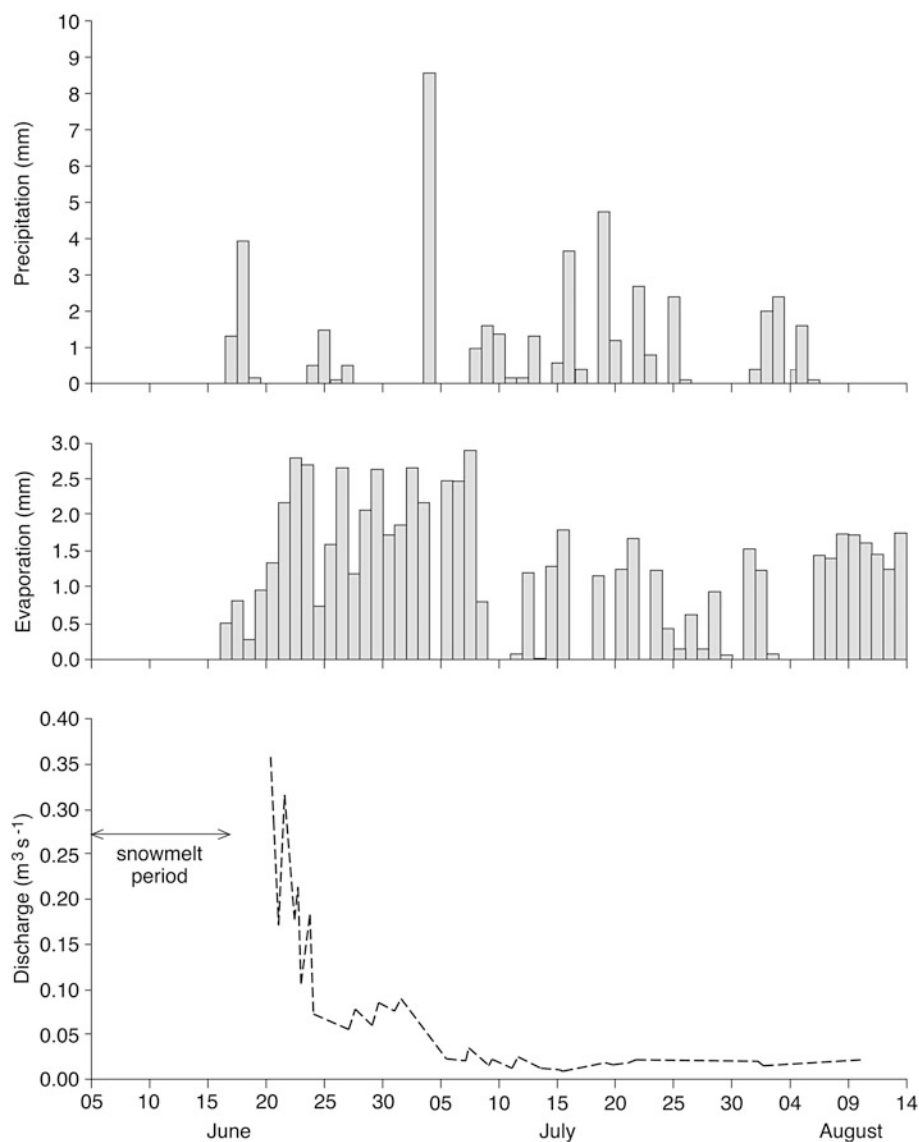
The frequency and duration of rainfall are important in the summer water budget, especially for ponds and wet meadows that do not receive reliable lateral water inflow. The amount of summer rainfall, as well as summer temperature, varies considerably from year to year, and extreme drought or wet events are experienced by Arctic wetlands (Young and Woo, 2003). Late summer rain can recharge ponds to snowmelt season levels, while streamflow may rise again in periods of intense or protracted summer rain. However, with a reduced storage status, the wetland becomes more effective in attenuating stormflow than it does with the spring freshet. Depending on antecedent moisture conditions and the amount of rainfall, Arctic wetlands may or may not show discharge



Wetlands of the Canadian Arctic, Figure 5 Between-year variations (2005, 2006) in the timing and duration of snowmelt due to differences in weather conditions at wetland sites in a polar oasis near Eastwind Lake, Ellesmere Island, and in polar desert at Creswell Bay, Somerset Island.



Wetlands of the Canadian Arctic, Figure 6 Uneven depletion of snow cover on the wetland and its surrounding dry lands during the melt season of 2010 at Polar Bear Pass. Residual snow and ice remains on the wetland at the time of the freshet, blocking or diverting the path of flow.



Wetlands of the Canadian Arctic, Figure 7 Outlet discharge (spring 2005) from wetland terrain near Creswell Bay, Somerset Island (see Figure 3), in relation to precipitation inputs and evaporation losses. The main snowmelt period is indicated (June 5–17, 2005).

response in the rainy period. By early winter, wetland streams stop flowing, or if a large river is fed by groundwater, baseflow continues under the river ice. The seasonal rhythm of streamflow, known as the wetland flow regime (Woo, 1988), is illustrated by the discharge of a small stream draining a low-gradient wetland complex near Creswell Bay (Figure 7).

Eventually, the wetland freezes as ground ice is formed in its saturated soil and pond water turns into ice. Sea ice formation lags behind river and lake ice, but coastal wetlands cease to be flooded when shore-fast ice is established. The snow that falls after wetland freeze-up is subject to redistribution by winds, often filling all

depressions and obliterating topographic irregularities on the wetland surface.

Wetland evolution and impacts of change

The natural evolution of Arctic wetlands follows some regular trajectories. Zoltai (1988) generalized the evolution in several stages. Deglaciation leaves a landscape with low ridges and troughs, pitted with depressions that are isolated or linked by drainage channels. In some areas, previously glaciated or otherwise, the draining of lakes through breaching of their rims or through thermokarst process also creates shallow depressions. Wetlands are formed in the depressions with gradual peat accumulation.

Peat growth tends to be slow because the cold environment does not favor vegetation development. Over time, paludification (the process of peat expansion to cover previously dry land) leads to an extension of the peat cover beyond the confines of the original depressions. Continued peat growth can raise the wetland above the regional water table, and a perched water table is formed within the peat. For Arctic wetlands, another process is also common, i.e., the growth of ground ice that heaves the peat into mounds and plateaus. These raised features retain or shed water to their surrounding wetlands.

In Arctic regions, there are close relationships among the evolution of peat and wetlands and development of permafrost. Woo and Young (2003) postulated that reliable local water supply in a semi-arid Arctic environment sustains a high water table that supports the growth of hydrophytic vegetation. Peaty materials accumulate when plants die and the peat provides insulation to the underlying ground ice against summer melt. Eventually, increase of ground ice in the soil leads to permafrost aggradation together with thinning of the active layer. Then, the shallow thawed zone would need only a small amount of water for its saturation, and this facilitates the maintenance of the wetland. These feedback mechanisms are self-perpetuating unless interrupted by natural or human disturbances.

Sea level change can alter the supply of water to coastal zones when gradual uplifting of the land deprives the coastal wetlands of frequent floods or can enhance flooding when coastal areas are subject to submergence. Geomorphic processes such as mechanical and thermal erosion, and shifting of shoreline and river channels, may alter the drainage pattern so that an existing wetland is lost to erosion or is left dry. Wild fire is a large hazard in the forested subarctic but is less so in the Arctic, though tundra fires have been observed. Climate warming, however, can affect wetlands on a regional scale. With early melt and perhaps a reduction in snowmelt water supply and increased evapotranspiration, wetlands become more prone to summer droughts and the peat risks accelerated decay. Wet meadow vegetation may convert to woody species, eventually altering grazing patterns of arctic ungulates (Hill and Henry, 2007) and loss of breeding habitats for wildlife, especially migratory birds.

As resource development and human settlements push northward, anthropogenic activities have impacts that may outpace natural changes. Mining activities can strip away protective wetland peat covers, exposing pockets of ice-rich permafrost to rapid thaw, leading to ground subsidence as well as the release of carbon and nutrients locked in the soil. Depending on the size and extent of the disturbance and characteristics of the underlying materials (soil texture, ice content), thermokarst or melt subsidence may produce new depressions prone to wetland formation. One leading concern for the Low Arctic is the risk of oil spills from both onshore and offshore exploration and production. This problem may be exacerbated by leakages from corroded pipelines due to

permafrost thaw and by incidence of oil spills in riverine and estuarine wetlands. Mining, oil and gas exploration and development also require a great deal of freshwater to support ice road and ice pad construction, for drilling mud, and domestic water supply. Depletion and contamination of water in the ponds, lakes, and streams by industrial uses can affect wetland water balance and quality and permafrost thermal regime, to the detriment of wildlife habitats.

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Cross-references

[Climate Change: Factors Causing Variation or Change in the Climate Wetlands](#)

[Wetlands: Classification, Distribution, Function](#)

WETLANDS: CLASSIFICATION, DISTRIBUTION, FUNCTION

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Introduction

Wetlands constitute a large variety in types and several classifications exist. Basic is hydrological conditions such as those providing hydrophilic vegetation to prevail. Water-saturated conditions often exist with direct connections between groundwater aquifers and wetland waters, i.e., open aquifers. In wetlands, saturated water conditions prevail near the surface with a water level close under the soil surface or often being at that level or even higher making up shallow surface water bodies.

Wetland functions in the landscape relate to environmental services and enhancing biodiversity conditions. Ecological functions besides those related to high biodiversity addresses water resources as contributing in the water balances and also water quality. However, wetlands often support high water content and turnover but also in drought conditions might store water being unfavorable to surrounding water bodies and downstream water courses. Regarding water quality, wetlands act as accumulation and sedimentation areas storing many chemical elements, especially base cations and metals but furnishing organic compounds and protons, meaning relatively high hydrogen and carbon release in relation to surrounding land. This would provide fairly high water color, with, in relation to surrounding land, often low pH.

Further, important functions of wetlands are storage of organic matter and thereby carbon; with the presence of sinks for carbon dioxide but in relation to greenhouse gases, there might instead be natural release of methane

or/and nitrous oxide turning the wetland into a source for gases when related to warming potential. The emissions of gases are though dependent on nutrient status and with higher nutrient level, the natural release of gases will be higher, also considering carbon dioxide being stored more comprehensively in poor sites.

Wetland types

The wetlands actually cover a wide range of water-related habitats, and internationally, probably the Ramsar convention 1971 would be the most well-known classification (Matthews, 1993). Wetlands here cover areas from the oceanic types where coastal areas with water depth up to 6 m at low tide are included. Vast areas would be considered in this context. In the Nordic region and also in North America, changes in land level due to isostatic and eustatic processes influence formation, especially related to coastal wetlands. Land-lift furnishes building up conditions while subsidence would have deteriorating impacts. Further wetlands are shallow inland waters, being limnic wetlands related to freshwater, and water courses, swamps, and marshes (Rydin and Jeglum, 2006). Turning closer upland to terrestrial types there are wet meadows, inundation areas, mires, and peatlands.

Wetlands include as mentioned above many types of moist and wet habitats. Those mainly being made up of actual water bodies would be sorted as wetlands while the types where organic matter has accumulated form mires and peatlands, and open water only exists on small parts of the whole peatland.

Geographical distribution of wetlands

Wetlands, covering 6% of the world's land area (Maltby, 1986), are of course abundant to water bodies and therefore coastal areas around the globe furnish the main part of wetlands, and these areas are often fairly highly populated and it is considered that two third of the world's population are living in connection to and being dependent on wetlands. Probably, these are of the types being more or less open water bodies while the number of people in peatland areas is fewer.

The geographical location of peatlands shows a distribution dominated by high latitudes on the Northern hemisphere where in the temperate and cold belt 90% of the peatlands of the world exist. However, peatlands are found more or less around the whole globe but preferably in areas related to high humidity while arid areas mainly lack peatlands. In parts of the world outside the high latitudes of the northern hemisphere, other types of peatlands may form, and in tropical regions, there are tropical peatlands, being, to a large extent, formed from wood debris and other macroorganic substances. These areas are often found in connection to larger water bodies such as the sea, big lakes, or rivers.

The areal coverage of peatlands extends over 3% of the land area of the world, and countries with territories in the boreal zone dominate the hosting of peatlands. Large areas such as Canada and Russia host 43% and 25%,

respectively. In third place, there is a part of USA, i.e., Alaska with 13%. However, already in the fourth place a country outside the northern part shows a peatland area of 7%, i.e., Indonesia with tropical peatlands. Other, bit smaller countries follow with Sweden making up 3% of the world's peatlands, i.e., c. 10 Mha, while Finland, Suomi, meaning mire land, with c. 9 Mha with a coverage of 2% anyhow includes the largest proportion of peatland of the country area with about 33%. A neighboring country, Estonia, with a territory of only c. 45,000 km² has a peatland share of 22% making up about 1% of the world's peatlands (Lappalainen, 1996).

Peatland development

Peatlands are often also referred to as mires but could not be considered synonymous as mires are defined as areas with hydrophilic vegetation and ongoing organic matter accumulation. Often there is also a restriction on organic matter thickness as referred to peatlands where 0.3 m is often considered required thickness to qualify as peatland. Mires are not limited by thickness and actually peat could be formed in more shallow layers than 0.3 m. Peatlands, on the other hand, have stored peat for some time but might be under land-use, such as forestry or agriculture, often requiring drainage and turning the natural organic matter accumulation into decomposition without ongoing peat accumulation.

In formation of peatlands, three main types of processes are considered, and it is interesting that both decreasing and increasing wetness may form peatlands. The most direct formation type is what is called primer peat formation, directly from a shoreline when water is retreating and could be found in sea shorelines. Secondly, the sedimentation and overgrowing of open water bodies is a rather common formation referred to as terrestrialization. However, the third formation is somewhat opposite where the mineral soil surface often in small depressions are more or less sealed by fine material providing water storage where peat-forming vegetation may colonize and organic matter accumulate. Such processes are called paludification, which actually make the landscape more wet. This type is most common and forms organic matter coverage of the landscape providing possibilities to expand and increase the peatland coverage. It should be kept in mind that peat formation in large parts of the northern hemisphere has been an ongoing process since the last ice age and peatlands that formed during that period still exist there now. This process has so far not stopped.

Peatlands are built by organic material first being deposited in shallow water bodies such as lakes and seashores. With time, new plants grow and decay, store organic matter continuously, and would be decomposed only a little because of lack of oxygen. Such conditions relate to water saturation and stagnation which is crucial for low decomposition and net accumulation of organic matter. In later stages, where storage has been ongoing, open water bodies will be overgrown and eventually such

surface water and groundwater fed habitats get colonized by plants with high water storage capacities. Such types are dominated by *Sphagnum* mosses storing precipitation efficiently, providing possibilities to grow higher and higher, leaving the contact with the mineral soil groundwater and mainly being fed by poor precipitation water. Then a bog is formed with the typical poor vegetation dominated just as mentioned by *Sphagnum* mosses and with only precipitation water input. Often such bogs are surrounded by a lagg area, actually being a groundwater-fed system where there is discharge from both mineral soil groundwater from surrounding uplands and bog water from the higher lying bog formation. Together, such combinations of bog and lagg fen form mire complexes of bog type.

Mainly wetlands are formed in locally low-lying land, often formed as depressions and the origin comes from high groundwater levels. In later stages, as described above, the accumulation of organic matter could turn the types into raised bogs being supplied by solely precipitation. In some cases though, with high precipitation often in mountain areas, peat may be formed mainly because of the excess humidity, and peatland could spread and cover the landscape following the contours and forming blanket bogs common in areas with maritime connections such as Ireland, Scotland, and Norway.

Mainly, however, peatlands depend on groundwater conditions and types depend on the origin of the water. Inflow of water provides prerequisites for the types developed and characteristic properties would prevail as described by Dembeck and Oswit (1996). Besides the fluvatile wetlands described below there are:

- Soligenous mires receiving discharging groundwater entering the area from upland mineral soils
- Water head peatlands with groundwater under piezometric pressure
- Oozing water peatlands with a more diffuse groundwater flow
- Topogeneous peatlands with water entering as groundwater or overland flow to local, partly isolated landscape depressions
- Bogs being fed by precipitation

Peatlands of fen type are formed in connections to inundations. Rivers may form other inland wetlands especially in low-lying areas being temporarily inundated at high flows, such as at spring snowmelt when the water level may rise several meters. These kinds of wetlands would be called fluvatile wetlands often extending over large areas of river shorelines. In connection to lakes these would also temporarily have high water levels, and low-lying surrounding land is inundated with wetland characteristics and peat formation.

Hydrological functions of peatlands

Peatlands are often divided into two main groups, i.e., fens and bogs. Related to water bodies, in bogs pools would be found but constitute relatively small areas and are surrounded by fairly large organic matter areas. As

mentioned above, water input to peatlands could be from different sources. Fairly high precipitation, at least in relation to evapotranspiration, would be a prerequisite. Direct precipitation to the land surface adds water to the system and bogs are totally dependent on this atmospheric inflow. However, groundwater in deeper layers provides a hydrological situation where the bog water would be kept in the formation for long time. The water flow in such areas most often are from the surface down into the lower layers of the soil forming what is hydrologically called inflow or recharge areas. In fens, water is of course also added from precipitation, but more importantly there is a direct inflow from surrounding groundwater meaning surface water formation in discharge areas. Outflow from such fens, then would be a mixture between rain water and groundwater.

Hydrochemically the bog water would be fairly poor in nutrients, and with a soil formed by *Sphagnum* plants, the pH would be low. Actually, bogs are acid with pH values around 4. Fen water, however, depends on the type of feeding groundwater and the mineral upland soils. There could be mainly silica sands and then the fen vegetation would be similar to bog vegetation and water nutrient poor. Often though, medium rich bedrock has formed a mineral soil keeping the water quality on medium nutrient richness with pH values between 5 and 6. Higher values may prevail in areas with calcareous bedrock or soils where pH could be up to 8 with a rich flora.

Water turnover in peatlands mainly are slow because of low hydraulic gradients and conductivity. Only in surface layers, the acrothelm (Rydin and Jeglum, 2006), higher conductivities occur providing high outflows in situation with excess water. In fens, such high water levels might prevail for longer periods due to inflowing groundwater from the uplands. In bogs, the high water flows are short-lived and directly dependent on input by precipitation. A short time after ceasing input, water levels are lowered into the somewhat deeper layers in a 0.2–0.5 m depth, the catohelm (Rydin and Jeglum, 2006), where hydraulic conductivity is low providing small or almost no water flow. This means, in wet situations peatlands provide high flows but in drought the water is mainly stored in the peat and the contribution to surface waters is withdrawn. The considerable contrast in water flows are more pronounced in peatlands as compared to mineral soils having better possibilities to maintain at least low water flows and a little water to water courses.

However, as a wetland element in the landscape, peatlands contribute to the biodiversity by being mainly a wet body in a drier landscape and thereby furnishing special and valuable hydrological conditions.

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Cross-references

[Fens, England](#)

[Wetlands](#)

[Wetlands of the Canadian Arctic](#)

WIND WAVES

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Synonyms

Water waves; Waves; Wind sea

What is a wind wave

Oscillations of a (water) surface can be generated by a large variety of reasons. In this chapter we will describe the ones due to the action of wind on the surface, their generation, evolution and effects.

The basic idea of a wave is a regular sinusoidal oscillation of the surface, this oscillation being characterized by height H , period T (hence frequency f and length L) and direction. In deep water, i.e. on a depth larger than half the wavelength, period, frequency and length are related by

$$f = 1/T \quad L = (g/2\pi)T^2 \quad c = L/T = (g/2\pi)T \quad (1)$$

with g the gravity acceleration and c the phase speed or celerity.

It is everybody experience that the appearance of a water surface under the action of wind is not regular. Rather, at a first glance it looks very confusing and chaotic. A more attentive look reveals some regularity in it, with dominant period and direction, and a characteristic (significant) wave height. These three quantities are connected to, and derived from, the full information available from the wave spectrum. The wave spectrum summarizes the surface conditions present at a given position or in a certain area. In general these conditions change in space and time, and so does consequently the spectrum.

Wave generation and development

When wind starts blowing on a water surface, at first very small ripples are generated. Soon these initially little waves grow both as height and length (hence period), and keep increasing till when the wind blows and is strong enough to sustain their growth.

Three processes concur to this development. The first one is the actual transfer of energy and momentum from wind to waves (Miles, 1957; Janssen, 2004). The higher the wave, the more effective is the transfer, so that the growth tends to be an exponential very effective process.

The presence of energy at different wave components and, under certain resonance conditions, the exchange of energy among the components, lead to a progressive shift of energy toward longer wavelengths (hence longer periods and lower frequencies). Because there is an obvious limit to the ratio height/length (hence steepness) of a given wave, this transfer allows larger wave heights to be present. This corresponds to the familiar increase of the wave heights while propagating under the action of wind.

A third process helps in keeping the system in balance. Wave breaking (white capping under the action of wind) naturally dissipates the excess of energy when single waves on the surface grow beyond their physical limit. For an ideal wave the theoretical limit is close to $H/L = 1/7$. In practice, due to the interaction among the various wave components, in a wind sea the limit is much lower, $H_s/L = 0.04$, with H_s the significant wave height and L the dominant wavelength.

As a matter of fact, most (more than 90%) of the energy put by wind into waves is rapidly dissipated by white capping. The actual growth of a wind sea is due to the positive difference between input by wind and wave breaking, with the energy transfer moving the peak period, hence wavelength, toward higher values.

The intensive breaking, or white capping, corresponds to the single, but highly frequent and distributed, white foamy crests that we see on a surface under the intensive action of wind.

On an infinite surface wind waves would grow till when the dominant waves move with a phase speed lower than the wind speed. Waves moving faster do not receive any direct input by wind. The time and space required to reach such conditions (fully developed sea, see Pierson and Moskowitz, 1964; Alves et al., 2003; Babanin, 2011) increase rapidly with the wind speed, reaching orders of many hours or days and hundreds or thousands of kilometers. In most of the cases, and more so in lakes and reservoirs, this condition is far from being achieved, and the wave conditions are limited either by the time the wind has been blowing (time limited) or by the amount of space available (fetch limited).

Waves propagate on the water surface. In deep water the crests move with c velocity (see Equation 1). However, energy, i.e., the wave system as a whole, moves with the group velocity that is only half this speed, i.e.,

$$c_g = c/2 = L/(2T) = (g/4\pi)T \quad (2)$$

Starting with the wave spectrum at given time and position, this implies that the different wave components of the spectrum propagate at different speeds. As a consequence, an observer far from the area of

generation will be reached first by the longer period (hence longer wavelength) waves, and progressively in time by the shorter and shorter ones. These waves have a more regular, often almost sinusoidal, appearance, and they are referred to as swell.

Waves in lakes and reservoirs

Given that, for a certain wind speed, the development of waves depends on fetch and time, it is intuitive that waves in a limited amount of space cannot reach the high conditions achievable on the large expanse of the oceans. Everything depends on the dimensions of the basin we are considering. Large basins as the Great Lakes of North America have dimensions comparable to that of some inner seas, and wave conditions can be comparably severe. However, also in relatively small lakes conditions can sometime be hazardous. The local hazard does not depend only on wave height, but also on the number of breaking waves. For a sustained wind speed, e.g. 15 m/s or more, this number is largest at the very early stage of generation. Therefore in a small lake under a strong wind possibly every single wave is breaking. Notwithstanding the limited wave height because of the short fetch, the surface will then appear as a continuous series of breaking waves that will make the navigation of small boats rather difficult.

Numerical methods for the evaluation of the wave conditions will be soon discussed. However, a simpler approach suffices for most of the small lakes to have an idea of the possible wave heights. In basins with limited dimensions we can assume with good approximation that the wind is uniform in space and time. In this case some simple relationships hold between the wind speed U , fetch x , and the dominant wave height H_s and period T (or frequency $f = 1/T$).

$$H_s = 2.88 \times 10^{-3} g^{-0.55} U^{1.1} x^{0.45} \quad (3)$$

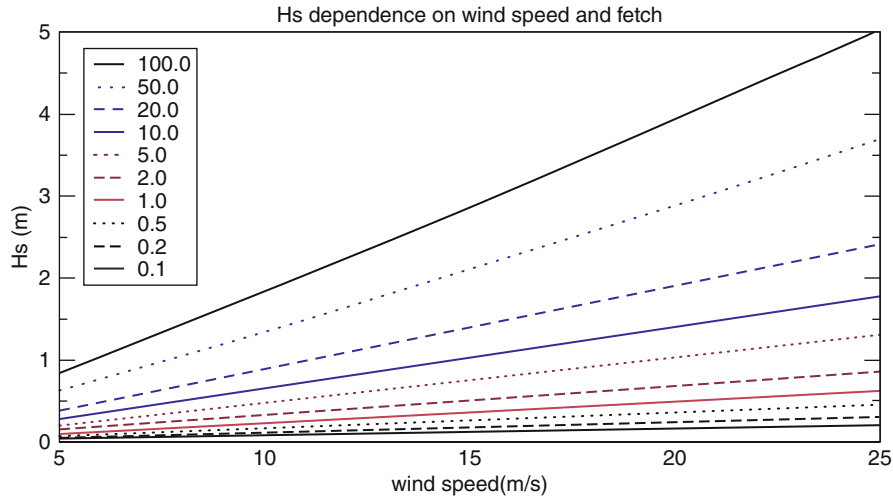
$$T = 0.459 \times g^{-0.73} U^{0.46} x^{0.25} \quad (4)$$

Derived from Equation 3, Figure 1 provides the maximum significant wave height as a function of wind speed U (m/s) and fetch x (km). In the figure the fetch (one line for each x) varies with an approximately geometric progression from 0.1 to 100 km. It is clear that, provided we are dealing with a large and prolonged storm, as it can indeed be the case, large basins can experience very severe storms.

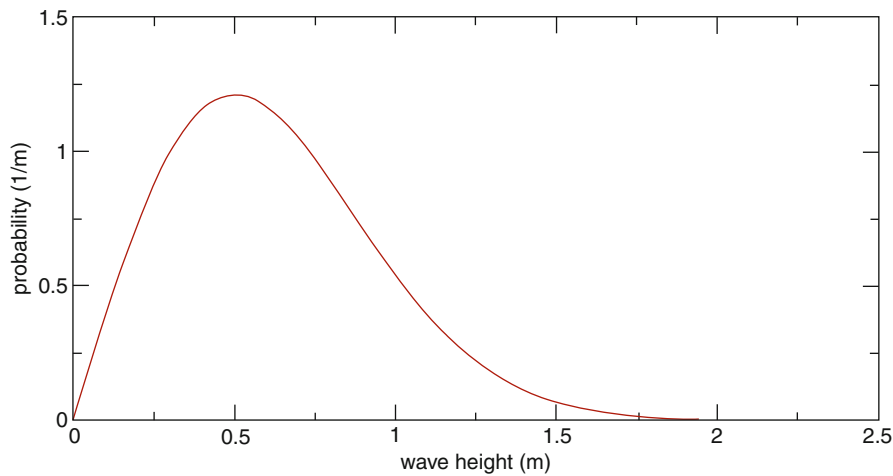
While the significant wave height H_s summarizes in a single figure the wave conditions at given time and position, smaller and larger single wave heights do exist. Their possible values are well represented by the Rayleigh distribution

$$p(h) = \frac{H}{4 \frac{H_s^2}{16}} \exp \left(-2 \left(\frac{H}{H_s} \right)^2 \right) \quad (5)$$

where $p(H)$ represents the probability of encountering a H high wave in a sea characterized by significant wave



Wind Waves, Figure 1 Maximum significant wave height (meter) as a function of wind speed (m/s) and fetch. Fetch (see legend) is expressed in kilometers. The fetch values, in an approximately geometric progression, increase from the lower to the upper line.



Wind Waves, Figure 2 Distribution of the probability of encountering single waves of height H in a sea characterised by 1 m significant wave height.

height H_s . As an example [Figure 2](#) shows the Rayleigh distribution for $H_s = 1$ m. It is worth noting that within the time of a few thousands waves, i.e., well within the duration of a storm, single wave heights as high as twice H_s are to be expected.

Kinematics, bottom and coastal effects

The presence of waves implies the motion of the objects on the water surface. For a sinusoidal wave the motion of a floating object is a circle with diameter equal to the wave height repeated with uniform velocity u every T seconds. It follows

$$u = \pi H / T$$

Surface motion implies also the motion of the underlying water layers. However, this motion attenuates rapidly with depth according to

$$d = H e^{-kz} \quad u = (\pi H / T) e^{-kz}$$

d being the extent of the motion and u the associated velocity. z is the depth we consider and k is the so called wave number $k = 2\pi/L$.

In practice at a depth equal to half the wavelength the motion is reduced to 4% of its surface value. At a depth equal to the wavelength there is hardly any motion left.

When waves move in shallow water, in practice when the depth h is smaller than $L/2$, waves feel the bottom. Their kinematics changes according to

$$c = (gT/2\pi)\tanh(2\pi h/L) \quad L = (gT^2/2\pi)\tanh(2\pi h/L) \\ c_g = 0.5c(1 + 2kh/\sinh(2kh))$$

In very shallow water these expressions simplify to

$$c = c_g = \sqrt{gh} \quad L = \sqrt{gh}T$$

The interaction of waves with the bottom has a double effect. On one hand it implies the dissipation of part of the wave energy, hence a reduction of their height. On the other hand, typically for sand or mud bottom material, it may lead to abundant suspended matter, hence to a change of the water characteristics, e.g., transparency or reflectivity.

Due to the dependence of wave celerity on depth, waves in deeper water move faster. In coastal and shallow areas this may imply the deformation of the long crests with possible focusing of the wave energy on certain zones. Refraction, as this process is called in relation to the similar process in optics, may lead to substantially larger, or smaller, waves in certain areas. Holthuijsen (2007) provides a good description of the process and suitable examples.

Measurements

A very large variety of instruments exists to measure water waves, the most convenient one depending on the wave conditions (typically wave heights) and situation we are dealing with. Moving from the low to the large wave heights, the possible instruments include capacitance wave gauges, laser beam, external or submerged acoustics, currentmetres measuring the orbital motion, submerged pressure transducers, and recording the motion of a surface following buoy. Some of these instruments require a fix support, either a pier or an offshore structure. Some others, as pressure transducers or currentmetres, when placed on the bottom and to be able to detect a signal, can be used only in shallow water. Buoys need to be moored on the bottom, but this is usually done till several hundreds meter depth. For large basins significant wave heights can be measured by satellite altimeters. Given the size of the ground area explored by each single measurement (a few kilometer diameter) and the spatial interval between adjacent orbits, this is only possible on large lakes.

Wave induced currents and turbulence

Currents in lakes may be due to the inflow of water at one end and possibly the outflow at another location. However, wind does have its profound effect on lakes.

Wind blowing over a water surface acts, via the intermediate generation and breaking of water waves, on the underlying layers. In a relatively short time, this leads to a current that attenuates with depth. The actual depth reached by the current increases with wind speed and time.

The effect can be much more intense close to the coast. Here incoming waves break, either because of shallow water or because they impact on the coast. If, as it is often the case, the wave direction is not perpendicular to the coast, their longitudinal component leads, via the coastal breaking, to a current adjacent and parallel to the coast. Combined with the associated suspended matter, this may lead to a substantial transport of coastal material, and consequent erosion and accumulation.

Via their surface breaking and their orbital motion below the surface, waves have a profound effect on the characteristics of the upper layers. In the lakes there is often, especially in the warmer periods of the year, a relatively warm upper layer on top of the deep cold one. The depth of the thermocline, the surface of discontinuity between the two layers, may vary from a few meters to several tens of meters in the larger and deeper basins. The underwater turbulence associated to waves may lead to a mixing of the two layers, to a consequent smoothing of the discontinuity and to an increase of the depth where we find the lower cold water.

Wave forecast

For a given geometry of the basin, water wave characteristics depend strictly on the wind conditions throughout the basin. The physics of generation, dissipation, evolution and transport of wave energy is a consolidated matter (see Komen et al., 1994; Janssen, 2004; Janssen, 2008; Babanin, 2011). Associated to the high quality meteorological forecasts presently available (see ECMWF for a full panorama of the latest statistics), this has allowed the development of sophisticated numerical systems for the forecast of water waves. Typically this is done at the global scale, which implies that only very large lakes can be considered, e.g., the Great Lakes of North America (see, e.g., Lalbeharry et al., 2009). Smaller lakes can be considered by numerical models running on limited areas, hence in general with higher resolution. Such an approach makes sense when the lake is large, and wind and wave conditions change appreciably from place to place. For smaller water surfaces a more pragmatic approach based on formulas Equations 3 and 4, or Figure 1, is frequently the most practical solution.

Summary

Wind generated water waves may reach substantial heights also in lakes. The height of waves increases increasing wind speed, fetch and time. Given two of these variables, the value of the third one will put a limit to the achievable heights.

Wave conditions at given time and position can be summarized into the local significant wave height H_s , mean period T_m and direction θ_m . For a given H_s different single wave heights can be expected, up to typically twice the significant wave height during the duration of a storm.

Waves lead to a number of effects on a lake: currents, suspended matter and its transport in shallow water (and)

close to the coast, a substantial mixing of the upper layers and possible reduction of the transparency.

Waves can be measured with a variety of instruments. The choice depends on the range of the expected wave heights, on the location (deep or shallow water, close to the coast or to a structure or offshore), and on the dimensions of the basin.

Sophisticated numerical systems are regularly used for wave forecast. For a given basin the necessary information is the evolution in time of the wind fields over the basin. While this is regularly done on the Great Lakes of North America, smaller lakes are considered in higher resolution models used on specific areas of interest. For smaller basins a direct evaluation, via the wind speed, based on general formulas relating wind speed U and fetch x may be a convenient solution.

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Hydrodynamics of Very Shallow Lakes
Sedimentation Processes in Lakes

WORLD LAKE DATABASE: INTERNATIONAL LAKE ENVIRONMENT COMMITTEE FOUNDATION (ILEC)

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Introduction

The International Lake Environment Committee Foundation (ILEC) (www.ilec.or.jp) was established in 1986. Since then ILEC has collected, in a systematic

manner, environmental and socioeconomic data of important (significant for human beings) lakes and reservoirs worldwide. Accordingly, the World Lake Database was constructed.

The World Lake Database

Currently the World Lake Database holds more than 500 lakes from 73 countries. The database was established in cooperation with UNEP.

The main data categories are:

1. Location
2. Description
3. Physical dimensions
4. Physiographic features
5. Lake water quality
6. Biological features
7. Socioeconomic conditions
8. Lake utilization
9. Deterioration of lake environment and hazards
10. Wastewater treatment
11. Lake improvement works
12. Development plans
13. Legislative and institutional measures for upgrading lake environment
14. Sources of data

A report of each lake providing the above categories can be obtained through a link in the database.

A search for a lake may be made by name, by country, by free word from: www.ilec.or.jp

The areas covered are:

- Africa
- Asia
- Europe
- North America
- Oceania
- South America

A typical lake report from the database gives:

- Lake name
- State
- Country
- Latitude
- Longitude
- Altitude (m)
- Surface area (m²)
- Volume (m³)
- Maximum depth (m)
- Mean depth (m)
- Water level control
- Normal range of water level (m)
- Length of shoreline (m)
- Residence time (year)
- Catchment area (m²)
- Hours of bright sunshine (h)
- Freezing period
- Mixing type

- Annual fish catch (t/year)
- Total N loading (t/year)
- Total P loading (t/year)
- Population
- Population density
- Water usage
- Land use

Cross-references

Arab Region, Lakes and Reservoirs
 Asia, Lakes Review
 Europe, Lakes Review
 Indian Lakes
 Japanese Lakes
 Russian Lakes
 South America, Lakes Review
 United Kingdom, Largest Lakes

WORLD LAKE VISION

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Concept of the World Lake Vision

The concept and necessity for the World Lake Vision (WLV) was developed by the Scientific Committee of the International Lake Environment Committee Foundation (ILEC, website: www.ilec.or.jp) at the second World Water Forum, which was held in The Hague, the Netherlands, in 2000.

The WLV was subsequently developed during 2000–2003 as a cooperative effort initiated by the ILEC, and was unveiled at the third World Water Forum, held in Shiga, Japan in March 2003.

Prepared during 2006–2007, the World Lake Vision Action Report (WLVAR) was published in 2007, as to follow-up to the implementation of the World Lake Vision.

The WLV has been accepted around the world as the guidebook for lake management, with the original English version having already been translated into eight different languages.

The earth's freshwater

The WLV points out that only about 2% of the earth's water is freshwater, and even most of it being locked up in the form of icebergs and glaciers, or else located deep underground beyond easy human reach. Nevertheless, even this relatively small proportion of the world's freshwater would be sufficient to satisfy the world's population if it were evenly distributed and protected from degradation, neither of which is the case.

The WLV indicated that lakes play a fundamental role in the global water cycle, and that more than 90% of all the liquid freshwater on the earth's surface at any given instant is contained in natural and artificial lakes.

Managing international lake systems

The WLV Report confirms that many lakes in the world are shared by two or more countries, a situation that can sometimes be a problem. The unsustainable use of water from a shared lake by one or more countries can result in international tensions.

Threats arising within drainage basins

Withdrawing or diverting excessive quantities of freshwater can reduce the water levels and volumes in lakes to the extent that their water quality and the biological communities they support can be seriously threatened. A dramatic example highlighted in the WLV Report is the demise of the Aral Sea as the result of the significant diversion of the lake's inflow tributaries for agricultural irrigation during the last 50 years. Another example is the water withdrawals by Israel, Jordan, and Palestine from the Dead Sea, the world's saltiest lake, is 417 m below sea level. Excessive water withdrawals from the Jordan River from both its north and south reaches has reduced the river's flow by 25%.

Excessive nutrient loads

The WLV Report notes that phosphorous and nitrogen are the primary nutrients that can cause cultural eutrophication, the accelerated growth of aquatic plants to nuisance levels, with accompanying degradation of water quality and interference with human water uses. Blue-green algae species are detrimental to both stock and human health, and can cause the production of trihalomethane precursors.

ILEC also developed "World Lake Database," in cooperation with UNEP, which includes data for more than 500 lakes from 73 countries.

The main data categories in the "World Lake Database" include:

1. Location
2. Basin description
3. Physical dimensions
4. Physiographic features
5. Lake water quality
6. Biological features
7. Socio-economic conditions
8. Lake water utilization
9. Deterioration of lake environment and hazards
10. Wastewater treatment
11. Improvement works in the lake
12. Development plans
13. Legislative and institutional measures for upgrading lake environment
14. Sources of data

A major contribution of the WLV is the development of seven guiding principles for managing lakes and reservoirs, as follows:

Principle 1: A harmonious relation between humans and nature is essential for the sustainable use of lakes.

Principle 2: A lake drainage basin is the logical starting point for planning and management actions for sustainable lake use.

Principle 3: A long-term, preventative approach directed at preventing the causes of lake degradation is essential.

Principle 4: Policy development and decision making for lake management should be based on sound science and the best available information.

Principle 5: The management of lakes for their sustainable use requires the resolution of conflicts among competing users of lake resources, taking into account the needs of present and future generations and of nature.

Principle 6: Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems.

Principle 7: Good governance, based on fairness, transparency, and empowerment of all stakeholders, is essential for sustainable lake use.

The seven principles identified above were used in analyzing the experience and lessons learned from a number of case studies by the WLV Committee, which was the basis for the subsequently developed WLVAR. The WLVAR focused on 27 lakes located in six continents. Six of the case study lakes were the largest in the countries in which they were located (Lake Chapala in Mexico, Laguna de Bay in the Philippines, Lake Poyang in China, Lake Biwa in Japan, Lake Taupo in New Zealand, and Lake Balaton in Hungary). The other case study lakes participating in the WLVAR were:

Asia

- Sentarum (Indonesia)
- Daecheong (Korea)
- Seven Crater Lakes (Philippines)

South Asia/India

- Bhoj Wetlands (India)
- Chilika (India)
- Hussainsagar (India)
- Powai (India)
- Lonar (India)
- Ujjani Reservoir (India)

Africa

- Victoria (Kenya, Tanzania, Uganda)
- Nakuru (Kenya)
- George (Uganda)
- Kariba (Zimbabwe)

Europe

- Constance (Austria, Germany, Switzerland)
- Baikal (Russia)
- Barton Broad (UK)

Latin America/Caribbean

- San Roque (Argentina)
- Fuguene (Columbia)
- Chapala (Mexico)

North America

- Champlain (Canada, USA)
- Kelly (USA)
- Waterford Impoundment (USA)

The Lake Baikal delta and a Slovakian impoundment also were included in the study (see Table 1 and Figure 1, both of which were reproduced with the kind permission of the WLV).

In reviewing the results of the case studies in the WLVAR, it was clear that not all the WLV Principles could be applied with equal ease, as shown in Table 1.

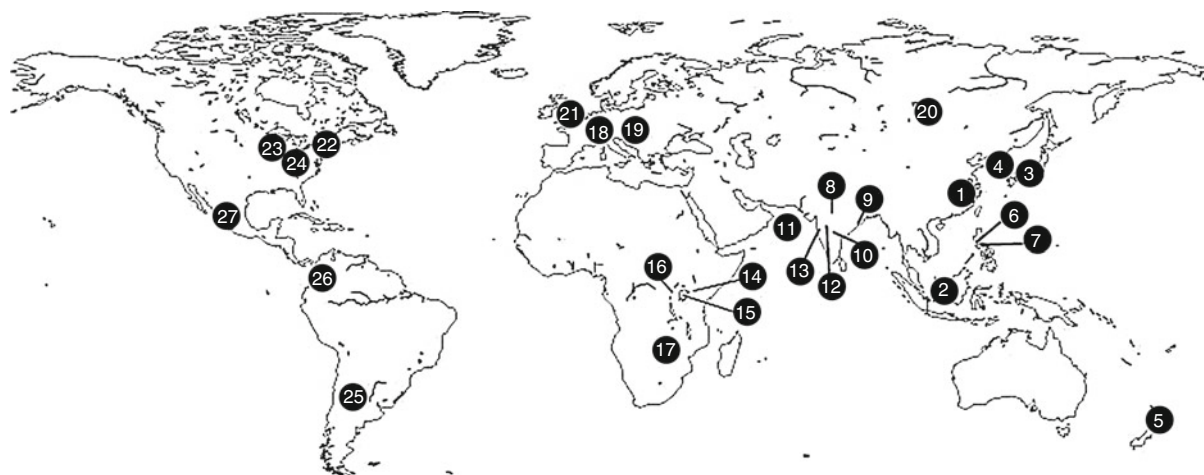
Since many of the lakes in the WLVAR survey have been studied prior to the development of the seven principles, the primary task facing the authors of the case study reports was to determine the extent to which the seven Principles could be used to guide lake basin management.

World Lake Vision, Table 1 Overview of easiest and most difficult WLV principle to implement in Lake Basin case studies

Region/lake	WLV principles						
	1	2	3	4	5	6	7
Asia/Pacific							
Lake Poyang		○			★		
Lake Sentarum	○				★		
Lake Biwa			★			○	
Daecheong Lake				○		★	
Lake Taupo		○			★		
Laguna de Bay				○			★
Seven Crater Lakes	★			○			
South Asia/India							
Lake Hussainsagar				○			★
Powai Lake				○			★
Lonar Lake				○			★
Ujjani reservoir				○		★	
Chilika Lake				○	★		
Bhoj Wetlands	○						★
Africa							
Lake Victoria							
Lake Nakuru	○						★
Lake George	○						★
Lake Kariba		★		○			
Europe							
Lake Baikal (delta)	○		★				
Lake Baikal ^a (lake)		○			★		
Lake Constance	○						★
Barton Broad		○			★		
Lake Balaton		○			★		
Small Slovakian impoundments (sediment management)			○				
North America							
Lake Champlain		○			★		
Kelly Lake		○					★
Waterford Impoundment						○	★
Latin America/Caribbean							
Lake Chapala		○			★		
Lake San Roque						○	★
Lake Fúquene			○		★		

Explanation: ○ = Easiest WLV Principle to implement; ★ = Hardest WLV Principle to implement

Because Russia is included geopolitically in the European region, Lake Baikal was included in the European case studies throughout this document, although the lake itself is located in Asia



- | | | | |
|----------------------|---------------------|---------------------|-------------------|
| 1 Lake Poyang | 8 Chilika Lagoon | 15 Lake Victoria | 22 Lake Champlain |
| 2 Lake Sentarum | 9 Lake Chlica | 16 Lake George | 23 Lake Kelly |
| 3 Lake Biwa | 10 Constance | 17 Kariba Reservoir | 24 Toba |
| 4 Lake Daecheong | 11 Lake Powai | 18 Lake Constance | 25 Lake San Roque |
| 5 Lake Taupo | 12 LonarLake | 19 Lake Balaton | 26 Lake Fuquene |
| 6 Laguna de Bay | 13 Ujjani Reservoir | 20 Lake Baikal | 27 Lake Chapala |
| 7 Seven Crater Lakes | 14 Lake Nakuru | 21 Barton Broad | |

World Lake Vision, Figure 1 Location of the 27 lakes of the case study in six continents.

The study results indicated that some of the Principles were easy to implement in most cases, while others were more difficult to implement. A general observation based to the WLV Report was that Principle 4 appeared to be the easiest Principle to implement for most of the case study lakes, while the most difficult to implement were Principles 5 and 7.

Implementing the WLV

There may be some eight million lakes in the world today. Many are well known to us, while others may still not have been named. Further, some may be so remote that accessibility to them is difficult, while others may only have been seen from space. It is the purpose of the proponents of WLV, therefore, to disseminate information from as many countries as possible on the world's lakes.

"The world's lakes, which are a primary source and storehouse of the world's easily accessible freshwater, will be a critical arena in the great transition to a society which sustains itself without degrading and depleting its own natural foundation. Many of these lakes are already in jeopardy" (WLV, 2003).

The aim of the WLV is to highlight this growing concern with the world's lakes and reservoirs, and to identify the need to manage these important waterbodies for their sustainable use, including undertaking activities and programs to ensure their long term health.

Acknowledgments

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X

XIAOLANGDI RESERVOIR'S ROLE IN WATER AND SEDIMENT REGULATION

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Introduction

Xiaolangdi reservoir plays a significant role in flood control of the lower Yellow River and sediment reduction since it was built. With its construction, the flood prevention and sedimentation situation in the lower Yellow River has greatly improved. In addition it increases the available water for people along the Yellow River and related areas. Three water and sediment regulation experiments have been carried out using Xiaolangdi reservoir and other reservoirs to further realize the rules on water and sediment movement and make full use of flood water to scour the riverbed of the lower reaches of the river.

Xiaolangdi reservoir is located in the middle reach of the Yellow River, 130 km below Sanmenxia reservoir. The drainage area of the reservoir is about 694,000 km², about 92.3% of the total basin. The design objectives are mainly flood control, ice flow flood control, sediment reduction, water supply, irrigation, and power generation. With a total capacity of 12.65 billion cubic meters and a live storage of 5.1 billion cubic meters and a population of 200,000, the reservoir enables the flood prevention standard to be improved from one flood in 60 years to one in 1,000 years. With joint operation, the reservoir plays an important role in sediment trapping and the formation of the lower river channel. During 2002–2005, four water and sediment regulation investigations were carried out and about 0.3 billion tons of sediment have been transported into the sea.

Xiaolangdi reservoir's role in harnessing of the Yellow River

The main objectives of the project are to:

1. Control flooding and ice jamming in the lower reaches in the Yellow River Basin to protect people and infrastructure
2. Control siltation in the 800-km downstream channel and prevent further aggradation so that levee raising can be delayed or controlled by 20 years
3. Provide water for assured irrigation for two million hectares and water supply to the cities and industries
4. Generate hydropower, replacing thermal generation in Henan Province and the Central China Power Grid

The project generates enormous benefits as follows:

1. Flood control measures significantly reduce the risk of major floods, normal annual floods, and ice-jam-related breaches of river embankments. The benefits are in terms of damage reduction to agriculture, urban, and industrial areas.

Some 100 million people benefit from protection of large floods and about three million people from annual and frequent floods (one in 5 years or less).

2. Benefits from sediment control are also significant, consisting mainly from reduced expenditure for embankment raising and maintenance.
3. Power benefits from peak power generation and avoiding the building of alternative thermal generation using gas turbines or other sources.
4. Irrigation and water supply benefits raising the yield of crops (mainly grain) to about double their present production and intensity of cropping over some 2 million hectares. More water is thereby made available to cities such as Qingdao and avoiding industrial output.

Flood control

Xiaolangdi Reservoir is located in the outlet of the last gorge of the middle yellow River below which is the large plain formed by the Yellow River, Huahe River, and Haihe. The significance of the Xiaolangdi site is that it controls over 90% of the basin. With the reservoirs Longyangxia, Liujiaxia, Daliushu, Qikou, Guxian, and Sanmenxia, the integrated planning of the Yellow River management with the formation of seven key engineering works.

The main objective of flood and ice control is based on the convenient geographical position and large reservoir capacity.

After the Xiaolangdi reservoir is operational, it cannot only store floods from reaches between Sanmenxia and Xiaolangdi but also reaches from Sanmenxia. When the reservoir is operated jointly with Sanmenxia, Guxian, and Luhun reservoirs, if a flood of frequency of one in 1,000 years occurs, the discharge at the Huayuankou gauging station won't exceed the present designed flood control standard of 22,000 m³/s; if a flood of frequency one in 100 years occurs, Dongping lake water detention area is unnecessary to be put into operation and the discharge at Huayuankou can be controlled below 15,000 m³/s.

Xiaolangdi reservoir mitigates the burden of the Sanmenxia reservoir. The chance of storing water in Sanmenxia reservoir can be reduced, which significantly slows the sedimentation in the reach to Tongguan.

The Xiaolangdi reservoir has significantly improved the flood control situation in the lower Yellow River, and the flood discharge ability is greatly improved in the Shandong reach. Since the reservoir was put into use, four water and sediment regulations have been carried out. During 2002–2004, large amounts of scoured sediment were transported to the sea. As a consequence, sedimentation has been improved and the flood discharge ability of the river improved. Water levels in the rising reach were 0.49–1.00 with discharges of 2,000 m³/s in 2004, lower than in 2002. Bank-full discharges improve from less than 2,000 m³/s to more than 3,000 m³/s. In 2003, six floods occurred in the Yellow River. In the rivers Jinghe, Weihe, Liluo, and Qin but with the joint regulation of Xiaolangdi, Sanmenxia, Luhun, and Guxian, the flood peaks are reduced, and the peak discharge at the Huayuankou gauging station is controlled at about 2,500 m³/s. Large areas of the floodplain were prevented from inundation and flood prevention pressure was relatively less.

Sediment reduction

Xiaolangdi was designed with the function of sediment trapping and can trap some ten billion tons of sediment. The period of sediment trapping can last 20 years. About one third of sediment of the Yellow River (0.5 billion tons) was silted annually in the reservoir. If combining other measures such as warping in Xiaobeiganliu (the main stream from Yumenkou to Tongguan), the period may even last longer.

With long-term water and soil conservation measures such as returning fields into forests and planting trees and grasses in the loess plateau which is the most serious area of soil erosion, a complete sediment disposal plan with different stages and different focuses has been formed. To store water in the reservoir before 2020 will be an effective way to reduce sediment in the lower river channel. The reservoir releases clear water to scour the lower river channel, and the sediment scoured in Baihe-Lijin reached as much as 0.172 billion cubic meters in the year 2000–2001 or about 0.5 billion tons.

Water supply

With 4 billion cubic meters or so capacity for flood control, the Xiaolangdi reservoir plays the role of flood control in the flood season and regulates runoff in the low flow or dry weather season. On average, there will be 2.6 billion cubic meters more water for water supply. This will ensure supply to cities and villages along the Yellow River and Central Plains Oilfield and Victory Oilfield and provide water to Shandong province in the dry weather seasons. In addition it will enable to transfer water to Tianjin of which ten times of the previous amount has now been transferred from the Yellow River, amounting to about 0.9 billion cubic meters each time.

Power generation

The installed capacity of the reservoir is 1.8 million kw, and the designed annual power generation is of the order of 5.1 billion kw.h. In 2004 the water efficiency was further improved. The water-discarding ration was reduced to 13.5%, and annual power generation was up to 5 billion kw.h. From 2001–2004, the total power generated was over 14.5 billion kw.h. The reservoir also plays an important role in the Human electricity network.

Three water and sediment regulation experiments

Several water and sediment regulations have been carried out with joint operation of the Xiaolangdi reservoir as well as other reservoirs in the mainstream and branches of the Yellow River. The so-called water and sediment regulation will form a suitable relation between water and sediment so that sediment discharging efficiency can be optimized and more sediment may be transported into the sea with less water.

The first water and sediment regulation was carried out in 2002. Clear water was discharged from the reservoir, with designed discharge and sediment content, and some 66.4 million tons of sediment scoured into the sea. In 2003, a larger-scale water and sediment regulation was carried out.

With joint operation of Sanmenxia, Xiaolangdi, Guxian, and Luhun, together four reservoirs, muddy water discharged from Xiaolangdi reservoir and clean water from the Yiluo River joined suitably at the Huayuankou gauging station to form a flood with discharge of about 2,600 m³/s and sediment content about 30 kg/m³ so that

the optimum water and sediment relation can be realized. Within 12 days, approximately 0.12 billion tons of sediment was transported into the sea. Included in this sediment released from the reservoir is 74.0 million tons, and scoured sediment from the river channel amounts to some 45.6 million tons. During 3 years of experiments, water stored in Xiaolangdi reservoir was fully utilized and the sedimentation situation of the reservoir was improved. The river bed of the lower reach was scoured, and the rules of density, flow, etc., were further realized. In 2005, water and sediment regulation began as routine.

Conclusions

After Xiaolengdi reservoir was first put into use, it has subsequently played a significant role in flood control, ice flood control, sediment reduction, irrigation and power generation, etc. However, at present the planned Guxian reservoir is still under demonstration. Due to

the limited capacity and the rising elevation of Tongguan, Sanmenxia reservoir's operation mode is completely discharged for most of the time. The regulating capacity of the present reservoirs is still limited. Though the sedimentation situation of the lower Yellow River has improved, the secondary suspended river phenomenon is still very serious. In addition, there is still a large area without controlling engineering works in the lower reach. With continuous dry years, the frequency of large floods threatens the safety of the people living in the floodplain; the flood control situation should be taken seriously.

Cross-references

[Chinese Lakes](#)
[Reservoir and Lake Trap Efficiency](#)
[Reservoir Sedimentation](#)
[Sediments, Flushing from Reservoirs](#)

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